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FLIGHT INVESTIGATION OF THE ROLL REQUIREMENTS FOR TRANSPORT AIRPLANES IN CRUISING FLIGHT

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16. Abstract

An airborne simulator provided a wide range of maximum roll control power (0.05 to 3.5 rad/sec^2) and time constants (0.1 to 10 sec) for pilot evaluation and rating. Roll criteria were developed and compared favorably with previously reported criteria. Maximum roll angular acceleration, maximum roll rate, roll time constant, time to bank, and bank-angle change in a given time all appear to be effective roll-criteria parameters. Steady-state roll rates of about 20 deg/sec and roll time constants of 1.8 seconds or less were required for satisfactory pilot ratings. With experienced test pilots, valid evaluation of single-degree-of-freedom roll response can be obtained with a fixed-base simulator.

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SUMMARY

An in-flight evaluation of roll handling for transport aircraft in cruise was conducted utilizing a general-purpose airborne simulator to provide single-degree-of-freedom roll dynamics. Maximum roll control power to 3.5 rad/sec^2 and roll time constants from 0.1 second to 10 seconds were evaluated and rated by five pilots in smooth-air conditions. Pilot evaluation and ratings were the important results from the study and provided the basis for the roll criteria that were developed and compared with other criteria. Pilot response to a well-designed questionnaire was effective in developing the roll criteria.

Maximum roll-control angular acceleration, maximum available roll rate, roll time constant, and bank-angle change in a given time all appear to be effective roll-criteria parameters. A steady-state roll rate of 15 to 20 degrees per second and roll time constants of 1.8 seconds or less were required for acceptable and satisfactory pilot ratings. Optimum pilot ratings were given for a roll capability of about 40 degrees per second with a time constant of 0.3 to 0.4 second. A wide range of roll response per unit of wheel control travel was rated satisfactory. Transport cruise rolling could be accomplished with very low levels of roll damping with increased pilot attention and compensation.

The roll criteria developed from this program were in general agreement with previously proposed roll criteria.

INTRODUCTION

The roll requirements for fighter and other highly maneuverable types of airplanes have been studied in some depth with airplanes and with moving and fixed-base simulators. Creer et al. (ref. 1) used a "roll chair" to provide rolling motion for a piloted simulation of up-and-away flight. The result was the definition of satisfactory, unsatisfactory, and unacceptable regions of roll-control power and damping for fighter airplanes in up-and-away flight. Only single-degree-of-freedom roll was considered, but the results have been verified to some extent in flight with variable-stability airplanes.

Other investigations extended these results by considering the effects of other variables on roll response. In reference 2, for example, a fixed-base simulator was used to consider the influence of aerodynamic coupling, control coupling, and airplane damping and stability on roll handling. From these results, pilot ratings may be estimated for a wide range of airplane types and missions. Pilot variability was also considered.

Theoretical studies have also contributed to the understanding of roll requirements. The study reported in reference 3 investigated the implication of roll-rate capability during attack and avoidance maneuvers and concluded that relatively low roll rates were required for maneuvering all types of airplanes. For a 2g turn, for example, only a 2-percent reduction in collision range was obtained with roll rates greater than 20 degrees per second, indicating that most airplane missions can be accomplished with relatively low rates.

A summary of roll handling-qualities research is presented in reference 4. Summarized are flight, simulator, and analytical considerations of the acceptability of airplane roll characteristics, including pilot gain required for the roll-control task. Roll control and response for transports were also considered, but there were little actual flight data to support the analysis and conclusions.

New airplane designs stimulate reviews of handling-qualities criteria and predictions of design acceptability. Reference 5 used a piloted simulator to predict the roll handling qualities of supersonic-transport configurations in cruising flight. Bisgood (ref. 6) and Leyman and Nuttall (ref. 7) reviewed handling-qualities research in an attempt to determine applicability for future designs. Roll-control criteria were considered and proposed as a result of these studies. Proposed revisions to the Military Specifications for piloted airplanes also provided the impetus for updating handling-qualities criteria. Recently, a comprehensive review and updating of Military Specifications were completed by the Cornell Aeronautical Laboratory (refs. 8 and 9). This investigation included the roll requirements for many classes of airplanes, but again showed little flight data on which to base roll requirements for transport and other large aircraft in up-and-away flight.

Several investigators have studied the roll control required for the approach and landing maneuvers of various types of airplanes (refs. 10 to 13). Roll criteria for acceptable handling were proposed in terms of bank-angle change in 1 second, time to bank, and roll-control sensitivity rather than roll-control power and damping proposed for up-and-away flight. Although the control required for the landing approach has determined the design for many types of aircraft, the intended operating envelope of present transport airplanes dictates that roll controls be designed for various parts of the flight envelope; thus, roll-control requirements are needed throughout the flight envelope.

The present program was planned to provide design information of this type for transport aircraft in cruising flight in smooth-air conditions. During the study, pilots evaluated the in-flight handling of a wide range of roll time constants and levels of roll-control power. Yaw coupling was minimized, and rudder control was not used. Longitudinal control and trim were used as required for constant-altitude turns. The variable-stability JetStar airplane, designated the general purpose airborne simulator (GPAS), was used to provide the in-flight piloting task for evaluation. The GPAS has a model-controlled simulation system which provides the capability of duplicating a wide range of airplane characteristics. The range of characteristics studied included the roll characteristics most likely to be considered in the design of either subsonic or supersonic transports for cruising flight. The results are presented as pilot evaluations and ratings and should provide basic data with which results giving the effects of other variables, such as turbulence and lateral-directional coupling, can be compared. Roll criteria are proposed and compared with referenced results.

SYMBOLS

e_p	roll-rate error, deg/sec
e_β	sideslip error, deg
$e_{\dot{\beta}}$	sideslip-rate error, deg/sec
e_φ	roll-angle error, deg
F_w	lateral wheel force, lb (N)
g	acceleration due to gravity, ft/sec^2 (m/sec^2)
$L_{\delta_a}\delta_{a_{max}}$	maximum roll-control angular acceleration or control power, rad/sec^2
L_{δ_a}	roll acceleration due to aileron control, 1/sec^2
p	roll rate, deg/sec
p_c	commanded roll rate, deg/sec
p_m	model roll rate, deg/sec
p_{ss}	steady-state roll rate, deg/sec
$(p_{ss})_{max}$	maximum steady-state roll rate, deg/sec
s	Laplace operator, per sec

t	time, sec
$t_{\varphi = 30^\circ}$	time to bank 30°, sec
δ_a	aileron-control deflection, deg
δ_{a_c}	commanded aileron control, deg
δ_{a_m}	model aileron deflection, deg
δ_r	rudder deflection, deg
δ_w	control-wheel deflection, deg
τ_R	roll time constant, sec
φ	bank angle, deg
φ_c	commanded bank angle, deg
φ_m	model bank angle, deg
φ_1	bank-angle change in first second, deg
φ_2	bank-angle change in first 2 seconds, deg
ω	frequency, rad/sec

EQUIPMENT AND SIMULATION

Description of GPAS

The general purpose airborne simulator is a Lockheed JetStar transport airplane with a model-controlled variable-stability system (ref. 14) installed to provide simulation capability. The general layout of the airplane is shown in figure 1, and a block diagram of the principal components of the model-controlled system is shown in figure 2. The evaluation pilot's control inputs are routed to the airborne analog computer through the artificial-feel system. The computer is programed with the equations of motion to be simulated. For this investigation the equation used in transfer-function form was simply

$$\frac{p}{\delta_a} = \frac{L_{\delta_a}\tau_R}{\tau_R s + 1}$$

Model response is compared with that of the JetStar, and the difference signal actuates the JetStar control surface to minimize the error. Roll rate and attitude were used as the control loops. With sufficiently high control-loop gain, the error is small and the computer model dynamics are reproduced closely by the JetStar airplane. The gains were:

$$\frac{p_c}{p_m} = 1.0 \qquad \frac{\delta_a}{e_p} = 1.0 \text{ sec}$$

$$\frac{\varphi_c}{\varphi_m} = 1.0 \qquad \frac{\delta_a}{e_\varphi} = 2.5$$

A model was not mechanized for sideslip, but sideslip and rate-of-change-of-sideslip loops were used to minimize sideslip. The sideslip gains were:

$$\frac{\delta_r}{e_\beta} = 6.0$$

$$\frac{\delta_r}{e_{\dot{\beta}}} = 2.0 \text{ sec}$$

The basic JetStar longitudinal dynamics for a Mach number of 0.55 and an altitude of approximately 20,000 feet (6,100 meters) were controlled in pitch by the pilot. The airplane's natural frequency at this flight-test condition in pitch was 2.55 rad/sec, and the damping ratio was 0.5. These longitudinal dynamics have been rated satisfactory during handling-qualities programs and so should not detract from the roll evaluation.

Displays and controls. — A special set of transport-airplane types of controls and displays were used by the evaluation pilot, who occupied the left pilot station. The controls for the left pilot station (fig. 3) were disconnected from the airplane control system, and the pilot "flew" the model on the analog computer of the simulation system.

In flight, the normal horizon and other outside peripheral visual cues were used by the pilot, and basic displays of JetStar heading, bank angle, pitch attitude, rate of climb, and sideslip were presented on the left pilot's panel (fig. 4). During ground simulations, the left pilot's panel displayed either model-response quantities or simulated JetStar response quantities.

The primary instrument display for the roll study was roll attitude. The response characteristics of the instrument are shown in figure 5. The ratio of actual roll attitude displayed to sine-wave inputs is shown in figure 5(a). Note that the response follows well but tends to be flat-topped, which could be interpreted by the pilot as a lag during the reversals at near peak oscillation amplitude; however, no pilot commented on the effect of the flat-topped response. The actual amplitude ratio (reflecting the flat-top effect) was constant over the frequency range of interest for this program (fig. 5(b)), and the phase lag (measured as if the response were sinusoidal) appears to be acceptable; it was less than 40° over the range of frequencies of interest for this program.

During the evaluations, the evaluation pilot maneuvered in roll and controlled in pitch as required. The artificial-feel system provided for him was an electrohydraulic control system designed to provide the capability of simulating a wide range of control-system characteristics. Applied force was detected by strain gages which commanded hydraulic servo position which, in turn, moved the control wheel to correspond to the applied force. The control position can be a function of preselected force gradients and nonlinearities; however, for these tests no breakout or hysteresis was simulated, and a roll-control gradient of 0.4 lb/deg (1.8 N/deg) was selected, with increasing force gradient at a wheel deflection of 60° (fig. 6(a)). (During one flight, the pilots selected force gradients for several flight conditions.)

The frequency-response characteristics of the roll-control feel system (fig. 6(b)) were determined by harmonic analysis of a pilot controlling with randomly varying frequencies to indicate the adequacy of the roll control for the program. The measured response can be approximated by an overdamped second-order system with a natural frequency of 10 to 12 rad/sec, which is typical of hydraulically actuated control systems.

The force gradient in pitch was 22 lb/in. (3.85 N/cm), which was described by one pilot as being lighter than that of most transports. Other pilots did not comment on the longitudinal force characteristics.

A delay time, which was a function of the time lag simulated, was noted and is discussed in some detail in a later section.

Data-acquisition system. – On each flight, approximately 40 parameters of more than 150 available were recorded on two 50-channel oscillographs. A 7-cps filter was used to attenuate high-frequency noise on the oscillograph recordings. Analog-computer model and JetStar responses, as well as pilot inputs and selected model-control systems parameters, were recorded. Some quantities were recorded twice with different scale factors for better resolution. A 12-channel direct-writing oscillograph was used for in-flight analog computer and GPAS following checks. A voice tape recorder was used to record all pilot comments.

GPAS Roll Simulation

A GPAS validation program indicated that the airplane/system was capable of high-quality reproduction of large-airplane model dynamic-response characteristics; however, a delay time was noted between model roll response and GPAS following in roll. Figure 7 presents examples of GPAS response to step commands of the model aileron control for the roll time constants investigated. Following requirements during actual piloting tests were expected to be less severe than the step commands of figure 7. Step control commands are not used by pilots in normal maneuvering. For a roll time constant of 0.1 second, figure 7(a) shows a delay lag of about 0.1 second between model roll rate and airplane following. Shifting the model roll rate and comparing it with the roll-rate response (second trace, fig. 7(a)) indicated following more typical of a higher order system than a simple time-constant response. However, the pilots were unable to recognize the order of the response, but did appreciate the fast response and commented favorably on the roll simulation. Evidence of slight turbulence is also apparent in the airplane roll rate.

Figure 7(b) illustrates roll-rate model following by the GPAS for a roll time constant of 0.35 second. Again, the model roll-rate trace has been shifted in time to give a better indication of the quality of reproduction of the model first-order response. A delay time of approximately 0.1 second is apparent before the JetStar responded in roll and, after a shift of an additional tenth of a second, the airplane response followed the first-order response of the model. However, shifting the model response an additional tenth of a second in figure 7(a) did not provide agreement between airplane and model response.

As roll-rate model response approached and became longer than that of the basic JetStar (the time constant of the JetStar was about 0.8 sec), following became more like first order (fig. 7(c) for $\tau_R = 1.0$ sec, fig. 7(d) for $\tau_R = 3.0$ sec, and fig. 7(e) for $\tau_R = 10.0$ sec). However, delay times were evident before the airplane roll-rate response matched that of the model for the low rates commanded in these examples. For the checks of the longer time constants, it was necessary to command low response rates in order not to exceed the bank-angle limitations of the JetStar, since it was desirable to obtain a recording of at least three time constants to achieve a good approximation to the steady-state roll rate.

The delay times (fig. 8) between the model roll-rate response and the JetStar roll-rate response were measured for the range of time constants of interest for this program and over a wider range of roll rates than could be obtained during the in-flight checkouts. Delay times were short, approximately one-tenth second, at short time constants and for high roll rates. As the time constant was increased and the commanded roll rate was decreased, the delay time increased. Delay times were less than 1 second for commanded roll rates as low as 2 deg/sec. No roll response was obtained for roll-rate commands of approximately 0.3 deg/sec or less.

As a part of each evaluation, the pilot was asked to demonstrate normal and fast roll rates for transport maneuvering. The rates demonstrated are indicated in figure 8 as the crosshatched regions. For low roll rates, the delay times for short time constants approached the value of the time constant simulated. Delay times for the long time constants were a much lower percentage of time constant simulated.

Question H on the pilot's questionnaire (table 1) asked whether objectionable lag existed between the control wheel force or displacement and the JetStar roll response. A summary of pilot response to the question is presented in figure 9. "No," "Yes," or "Slight" answers are summarized as functions of maximum steady-state roll rate and roll time constants. Lag in roll response was most often noted at the longer time constants than at the low roll rates, indicating that the pilots were probably commenting on the delay in roll-rate buildup or the effect of the roll time constant rather than the delay time which occurred without JetStar response. There were no specific pilot comments concerning the simulation-system delay time, nor were there comments concerning the order of the roll response not being a first-order lag.

The effect of lag in combined response was studied during the investigation of roll controls for transport airplanes in references 11 and 12. Control-system rate limits were adjusted during the study reported in reference 11 to allow full control in 0.4 second and 0.9 second. The change in rate limit had no significant effect on the pilot evaluation except as might be noted in the slightly reduced bank angle achieved with a given program of time-displacement wheel position. In reference 12, the control-system rate limit was changed to allow maximum control to be achieved over the range of 0.2 second to 1.4 seconds. From the investigation it was concluded that there was little effect on pilot rating up to a lag of 0.7 second, and there was a degradation in rating of only about one pilot rating number to the lowest rate limit investigated. The pilots described the degraded control-system response as an apparent increased roll time constant for the large wheel deflections. The results implied that the lag or delay time could be interpreted as a slightly increased roll time constant. From these results and the results of the pilot questionnaire in the present study, it was concluded that the delay time had little effect on the pilot ratings obtained and that the simulation was acceptable.

Conduct of the Experiment

The prime variables of the program were level of roll-control angular acceleration and roll damping or roll time constant. Roll-control angular accelerations ranged from 0.05 rad/sec^2 to 3.5 rad/sec^2, and roll time constants ranged from 0.1 second to 10 seconds. This resulted in steady-state roll rates of 1 deg/sec to a theoretically possible 2100 deg/sec, with a control-wheel and aileron deflection of about 60° available to the pilot.

Five experienced test pilots participated in the program. Three of the pilots flew 90 percent of the program, and two other pilots evaluated typical conditions. Although none of the pilots had experience as airline transport pilots, all were experienced test pilots with a varied background of flight test and evaluation experience, including large transport airplanes. All were familiar with handling-qualities evaluations and pilot rating scales. Four of the pilots were NASA Flight Research Center research pilots, and one was an engineering test pilot for the Boeing Company. Pilots A, B, C, and D had approximately 3000, 4000, 1000, and 500 hours, respectively, of flight test experience; they had 2500, 8180, 2800, and 250 flight hours, respectively, in transport or bomber types of airplanes.

The order of evaluating test conditions was selected randomly, and no pilot was aware of the test condition to be evaluated prior to the actual evaluation. Some conditions for evaluation were repeated, in some instances on the same flight; other conditions were evaluated as many as nine times during the program. A single pilot repeated evaluations of a test condition as many as four times, and each of the three primary pilots repeated evaluations of conditions at least three times to indicate pilot variability.

During checkout of the simulation, the pilots were acquainted with the goals of the program and the pilot questionnaires were finalized. Evaluations were conducted using the GPAS as a fixed-based simulator for pilot orientation and practice.

The following maneuvers were suggested for in-flight evaluation and, for the most part, were used by each pilot on each evaluation:

1. Make normal-rate banks to 30° bank angle, change heading 20° at constant bank angle, recover to level flight at a preselected heading.

2. Roll to 30° bank angle as rapidly as possible without overshooting 45° (attempt to use full aileron); stabilize at 30° bank angle as rapidly and precisely as possible; recover to level flight.

3. Bank to 30° bank angle in 10° steps, stabilizing at each 10° step.

4. Make slow and fast aileron reversals.

5. Make aileron steps of various magnitudes.

Each evaluation pilot was allowed to perform other maneuvers as desired and to maneuver the airplane as long as desired before recording answers to the pilot questionnaire (table 1) and giving an overall pilot rating (table 2). During each pilot's evaluation maneuvering or following his evaluations, the pilot demonstrated for recording a normal roll rate for transport operation and a fast roll rate, the maximum normally used in transport operation. These maneuvers provided additional insight into the roll rates the pilot expected of transport aircraft.

Before each pilot evaluation, the validity of the simulation was checked by recording the response of the analog-computer model to a step command of model aileron and comparing the model response to the response of a check case calculated prior to flight. With assurance that the model was correct, the response of the JetStar to the same step command was recorded. This response was analyzed for experimental roll-control power and time constant. These data are summarized in appendix A.

RESULTS AND DISCUSSION

Summary of Pilot Comments

Pilot evaluations and opinions were the most important results obtained from this program. Evaluation guidelines and a questionnaire were established during the first flight of the program. (The first-flight results are not included in the data presented.) On all subsequent flights the questionnaire (table 1) was used along with the pilot rating scale (table 2) for the overall evaluations. Brief key-word summary pilot comments for each of the questions are given in table 3. The flight conditions simulated in terms of set values of roll-control power and time constant and pilot numerical ratings are included in table 3. Typical detailed comments by individual pilots are given in appendix B. Because many of the questions could be answered quite simply, the comments were summarized as functions of the simulated response parameters (quantities set in the computer model), for example, control power, time constant, and theoretical steady-state roll rates.

In response to question B concerning the pilot's ability to roll to and stop at a given bank angle both slow and fast, comments such as "Good," "Acceptable," "Acceptable slow only," "Fair," and "Poor" were made by the pilots. The comments are summarized in figure 10. The region of characteristics considered to be good or acceptable is crosshatched and represents a compromise of roll response and damping. The change in roll-control power also manifested itself to the pilots as a change in control sensitivity.

Question D specifically asked whether the roll rate available was acceptable for a transport. The pilot comments in many cases indicated not only whether the roll rate was acceptable but also whether it was unacceptably high or low. Figure 11 summarizes these pilot comments in terms of maximum steady-state roll rate and shows a region of acceptable roll rates of about 20 to 70 deg/sec at the shorter time constants, with higher roll rates being acceptable at the longer time constants. Roll rates above and below the acceptable region were either too high or too low.

During the evaluations, the pilots were asked to evaluate the use of full wheel deflection or maximum roll rate available if possible and to comment on the use of full wheel or the maximum roll velocity developed. Figure 12 summarizes the pilot comments on the use of full wheel. Surprisingly, the pilots indicated that full wheel (i.e., 60°) could be used over a wide range of roll accelerations. They used full control in the regions of long time constants in a pulse-like manner (acceleration command) in an attempt to obtain the initial rapid roll rate desired; however, they did not allow the steady-state roll rate to develop to the maximum of which the airplane was capable. It was necessary to use full wheel at the lowest time constants where responses were highly damped and steady-state roll rate was low. In this region, the pilots objected to the high control forces associated with the large wheel deflection. Control sensitivity and steady-state roll rate were high at the highest levels of control power and longest time constants. Full wheel could not be used in these conditions.

The pilots were also requested to comment on the acceptability of the roll damping or time constant (question F). These data (fig. 13) show whether the time constant was acceptable and also whether the roll damping was considered to be high or low. A time constant of 1 second was generally acceptable, whereas 3 seconds was not acceptable, i.e., the damping was too low. More damping, or a shorter time constant, was generally preferred with higher control power. Although high damping was appreciated, one pilot considered the lowest time constant evaluated to be too low, too highly damped. He described it as not responding like an airplane. Time constants of 3 to 10 seconds were evaluated to be unacceptable because of the low damping, regardless of the control power; however, maneuvering at low roll rates could be accomplished with very low levels of damping with increased pilot attention and compensation.

When a wide range of roll-control power and damping is being investigated, there is the possibility of pilot-induced oscillations in some region considered. The pilots were requested to indicate (question G) whether there was any tendency for the pilot to induce oscillations or overcontrol. These pilot comments are summarized in figure 14. Most of the region of roll-control power and time constants investigated was free of any overcontrol tendency; however, the high control power, low damping region was reported to be prone to pilot-induced oscillations. The pilot had to use care in attempting to control rapidly. In all conditions simulated, the roll response was damped; however, the pilot overcontrolled in attempting to control precisely and commented that some of the longer time constants appeared to be divergent.

Although the wheel force gradients were changed for only a few evaluations, the roll response and damping were changed over a wide range, which gave the effect of a wide variation in wheel force per steady-state roll rate. The wheel-deflection limits remained the same ±60° throughout the program. Wheel deflection per roll rate can be obtained by applying a factor of 2.5 deg/lb (0.56 deg/N) to the data presented. Pilot comments in response to question J on whether the control-wheel deflection and force characteristics were acceptable for a transport are summarized in figure 15. From these data a region of about 0.3 to 1 lb/deg/sec (1.3 to 4.4 N/deg/sec) steady-state roll rate was evaluated to be acceptable with time constants of less than 1 second. Above the acceptable region, the control-wheel forces were too high and airplane roll response was too low. A region of 0.1 pound (0.4 newton) or less of force per unit roll rate was excluded as being too sensitive, with control forces too low. Lower force per roll-rate response was desired with longer time constants.

Because a transport pilot has many duties, question L requested an evaluation of the pilot's ability to control and maneuver the airplane with one hand. The results are presented in figure 16. A maximum wheel force per unit of steady-state roll rate of 1 pound (4.4 newtons) was acceptable for one-hand control. This implies that 20 pounds (89 newtons) of control force would be accepted to achieve the previously acceptable roll rate of 20 deg/sec. Most of the region acceptable for one-hand control had much lower forces per unit of roll rate, and it extended to the region susceptible to pilot-induced oscillations. Evidently, the pilots were willing to risk induced oscillations or overcontrol for the less effort required with low wheel force and high steady-state roll capability. It is interesting to note that the pilots accepted about the same force-response relationships for one-hand control as they desired for normal operation (fig. 15).

Pilot comments concerning the overall acceptability of the roll characteristics for a transport airplane (question M) are summarized in figure 17. Most of the comments were either "Acceptable," "Not acceptable," or "Marginally acceptable." The comments clearly define a region of roll-control power and time constant considered to be acceptable. Time constants evaluated to be acceptable were 0.1 second to less than 3.0 seconds, and maximum angular accelerations as low as 0.2 rad/sec^2 and to the limit of the tests, 3.5 rad/sec^2, were acceptable. In general, the acceptable region was a function of both parameters; however, time constants greater than 1 to 2 seconds were unacceptable. Steady-state roll rates of about 12 deg/sec to 120 deg/sec were rated acceptable. These results were obtained with a wheel- and aileron-deflection capability of about 60°, with a wheel force gradient of 0.4 lb/deg (1.8 N/deg). Wheel force and deflection were not changed for this part of the program, so there was an apparent change in roll-control sensitivity accompanying the changes to the response parameters.

Summary of Pilot-Rating Data

In addition to the pilot evaluations and detailed comments obtained for each flight condition, the pilots were requested to make a pilot rating based on the Cooper-Harper (ref. 15) rating scale of table 2 for the overall roll handling qualities. These results are summarized in figures 18(a) to 18(d) as a function of roll-control power and roll time constant for each program pilot. Generally, low roll-control power was rated poorer (higher rating number) than the high roll-control power, although both were unacceptable. The pilots desired maneuver capability and were reluctant to accept very low response rates. Short time constants or high roll damping were appreciated; however, there was a compromise between very short time constants and long time constants that resulted in satisfactory pilot rating. In general, the pilots were in agreement on desirable roll characteristics; however, pilot ratings are subjective measures and thus have variability. The variability of the ratings is discussed in appendix C.

Roll time constants. – Cross-plotting the pilot rating data (fig. 19) gives roll time constants for optimum pilot ratings. For a constant roll-control power of 2.0 rad/sec^2, optimum pilot rating was obtained for a time constant of 0.35 second. Pilot rating decreased rapidly with increasing time constant. Similar variations were obtained for the other values of control power.

The most favorable pilot ratings as a function of roll time constant are summarized in figure 20. Roll time constants of 1.8 seconds or less are indicated to be acceptable and satisfactory (pilot rating $\leqq$ 3.5), and time constants of about 5.0 seconds or less were considered to be acceptable but unsatisfactory. Comparison of these results with a summary of the data presented in reference 4 shows good agreement (fig. 21) in pilot rating level and variation with time constant. The referenced results included data from moving- and fixed-base simulations and some flight simulations.

The recently revised Military Specification for piloted airplanes (ref. 16) gives roll-response specifications in terms of roll time constant and bank-angle change in a given time. For transport airplanes, class III, category B, three levels of handling qualities are specified for conditions concerning the ability to complete the operational mission. Level 1 (as specified in ref. 8) handling qualities represent a pilot rating of 3.5 or better; level 2 represents a pilot rating of 6.5 or better; and level 3, a pilot rating of 9.5 or better. Comparison of the present results with the specified levels of flying qualities (fig. 22) shows the present pilot ratings to be more optimistic regarding roll handling with the time constants considered than the referenced interpretation of the Military Specification.

In the study of reference 5 a fixed-base simulator was used to consider roll handling qualities of a proposed supersonic transport in cruise. The supersonic-transport results for the roll time constants investigated showed more satisfactory pilot ratings than were obtained in the present study. For example, the supersonic-transport roll time constant of 4.7 seconds was rated acceptable, with pilot ratings of 3.5 to 4.0. Reduction of the roll time constants to 1.4 seconds for the supersonic transport resulted in pilot ratings of 2 to 3. These ratings were about 1 to 2 rating numbers more satisfactory than those obtained in the present study with a simpler, uncoupled control task. The control task, however, was similar, requiring only a correction in heading and maintenance of straight and level flight for a specified time.

Roll-control power. – The roll-control power for an optimum pilot rating was also determined from the pilot rating data and is presented in figure 23 for roll time constants of 0.35 to 10 seconds. Values of maximum angular acceleration from 2 rad/sec^2 to 0.7 rad/sec^2 were rated acceptable and satisfactory. There was a rapid deterioration in "optimum" pilot rating with decrease in control power below 0.8 rad/sec^2. An optimum was not defined at the shortest time constant investigated, τ_R = 0.1 sec (fig. 18).

Figures 20 and 23, which presented optimum pilot ratings, were combined to obtain optimum roll-response characteristics (fig. 24). A roll-control power of 2.0 rad/sec^2 and a roll time constant of about 0.3 to 0.4 second produced the best overall pilot rating. A roll-control power of 0.7 rad/sec^2 and a roll time constant of 1.8 resulted in a pilot rating of 3.5. Lower control power and longer time constants were rated unsatisfactory.

One flight was made during which pilots A and B selected roll time constants for the three values of roll-control power that provided the best overall roll response. The results are shown in figure 24, and typical pilot evaluation comments are included in appendix D. Only levels of control power predicted to give satisfactory handling were considered for evaluation. In general, the results of the special test substantiate the derived optimum roll-response characteristics.

Acceleration criteria. – Optimizing the pilot ratings for the roll parameters also produced boundaries that defined satisfactory and unsatisfactory pilot rating regions (fig. 25). High roll-control power with high damping (short time constants) produced satisfactory pilot ratings. Control power and damping reduced together produced satisfactory pilot ratings. A control power of less than 0.4 rad/sec^2 and time constants greater than 1.8 seconds were rated unsatisfactory. Much of the remaining roll-control-power/time-constant region was unsatisfactory, even to the limit of the time constants, 10 seconds, investigated. Low roll-response rates resulted in an unacceptable region at low control power and short time constants, and the region of extremely low roll-control power was rated to be virtually uncontrollable (pilot rating of 9.5).

Steady-state roll rate. – The roll-control-power data were converted to steady-state roll rate for comparison with other roll criteria. Typical pilot rating data (pilot B) are presented in figure 26. Very high roll rates were theoretically possible at the very long time constants. The roll-rate range was about 1 to 2100 deg/sec. The extremely high steady-state roll rates were not used because the bank angle of the JetStar was restricted to 60°, so the realized control limit was determined more by control sensitivity than by control rate at the high control power and long time constants. Evaluation of roll response in this region was affected by the lag noted by the pilots (fig. 9).

Cross plots of roll rate at constant roll time constant were made to determine the roll rates that were given the best pilot ratings (fig. 27). For the range of time constants of 0.35 second to 3 seconds, the steady-state roll rate varied from 40 deg/sec, with an average of the optimum ratings for the three principal program pilots of 2.2, to 90 deg/sec, with an average best rating (three principal pilots) of about 5.0 (fig. 28). The roll rates appear to be high for transports; however, they are for optimum pilot rating. Transport pilots seldom use high roll rate, but they do desire adequate roll power and roll-control sensitivity. Optimums were not defined at the highest and the lowest roll time constants tested (τ_R = 0.1 and 10 sec).

Roll-rate criteria. – On the basis of all the pilot ratings, satisfactory, unsatisfactory, and unacceptable regions of steady-state roll rate and time constant were determined and are presented in figure 29. The roll characteristics which resulted in optimum pilot ratings are also included. The steady-state roll rates which were rated best increased with increasing time constant. The pilot rating did, however, become less satisfactory as the steady-state roll rate and time constant increased. Minimum satisfactory roll rate appears to be between 15 and 20 deg/sec, which tends to agree with the conclusion of reference 3 that high roll rates are not required for maneuvering airplanes. A roll rate of about 5 deg/sec was required for acceptable but unsatisfactory ratings, and roll rates of less than 2 deg/sec were considered to be virtually uncontrollable.

During all the evaluation, the pilots were asked to demonstrate normal and fast roll-rate maneuvers that they considered to be acceptable for transport operation. When the roll-control power was very low, the pilot could only demonstrate slow rates, as was noted in the pilot comments. The fast roll rates demonstrated the maximum roll rate the pilot would normally use in maneuvering a transport. These data are summarized in figures 30(a) and 30(b) as histograms of the distribution of the roll rates demonstrated. The normal roll rates are concentrated about 3 to 6 deg/sec, with a mean of about 5 deg/sec. The fast roll rates, as fast as would normally be used, are concentrated from 10 to 25 deg/sec roll rate, with a mean of about 17 deg/sec. On the average, pilots demonstrated roll rates much lower than were rated optimum, but in the range rated to be satisfactory. The standard deviations of the roll rates demonstrated were similar, being about half the mean roll rates.

Other Criteria

The revised Military Specification (ref. 16) was given in terms of time to bank to specific bank angles characteristic of the mission phase being considered. In addition, the maximum roll time constants were specified. Other investigators of roll-control requirements for approach and landing have proposed criteria in such forms as bank angle in the first second and bank-angle sensitivity to control. The data from this program are compared with the results of the references cited.

Time to bank 30°. — In converting the data to bank angle, the effect of the delay time of figure 8 was included. Only the lower time-constant data of 0.1, 0.35, and 1.0 second rated to be satisfactory were used to exclude the effects of long time constant. Figure 31 illustrates the determination of optimum time to bank 30° made from ratings of pilot B. Similar results were determined for the other principal pilots in the program. The three pilots agreed that a time to bank 30° of about 1.5 seconds would be satisfactory (fig. 32) for transport operation. Maximum times of 2 to 3 seconds were indicated to insure a pilot rating of 3.5 or less. With somewhat less agreement among the pilots, the data indicated that times to bank 30° of 4.2 to 5.7 seconds or less would be required for a pilot rating of less than 6.5.

Figure 32 also compares these data with the proposed Military Specification (ref. 16) for time to bank for class III, category B transport aircraft. The military specifications were given in terms of levels of flying qualities, which were interpreted in reference 8 in terms of pilot ratings. Level 1 was interpreted to mean a pilot rating of 3.5 or better, level 2, a pilot rating of 6.5 or better, and level 3, a pilot rating of 9.5 or better. Reference 16 specifies 2 seconds to bank 30° for level 1, which was also predicted to be good by Ashkenas (ref. 4) and which agrees reasonably well with the pilot rating data from this program. Pilot C was the most lenient of the pilots, considering 2.7 seconds to bank 30° to be satisfactory.

Interpretation of level 2 as was done in reference 8 indicates that pilots of the present study were somewhat more lenient than the combined reference 16 and 8 specification. About 50 percent greater time to bank 30° was allowed by the present results than by the specifications.

Bank-angle change in time. – Optimum bank-angle changes in 2 seconds and 1 second were also determined.

Reference 4 concluded that bank angle obtainable in 2 seconds provided a somewhat better correlating parameter for transports in cruise conditions than bank angle obtainable in 1 second, which has been used for approach conditions. The results were converted to both parameters for comparison with various referenced results. Again, only data for roll time constants rated to be satisfactory (τ_R = 0.1, 0.35, and 1.0 sec) were used.

Figures 33(a) and 33(b) present pilot ratings for bank angles achieved in 2 seconds and 1 second for pilots A and C, respectively. Similar analyses were made for the other program pilots. The results for the three program pilots are summarized in figures 34 and 35. Optimum bank angle achieved in 2 seconds was about 50° to 60° (fig. 34) and was rated 2 to 3. Minimum bank-angle change in 2 seconds for a satisfactory rating was about 30° according to the evaluation of pilots A and B. Pilot C considered $\varphi_2 = 18°$ to be satisfactory. Most of the data from the program agree with the Military Specification (ref. 16) for transport airplanes, class III, category B, of 30° bank-angle change in 2 seconds. This requirement was also predicted to be "good" by reference 4.

Quite a wide range of bank-angle changes in 2 seconds is predicted to be acceptable, but unsatisfactory, by the present tests (fig. 34). The lower limit by pilots A and B for a pilot rating of 6.5 was about 12° in 2 seconds. Pilot C accepted 5° bank-angle change in 2 seconds for a rating of 6.5 or better. Only the data of pilot B indicated an upper limit for bank-angle change in 2 seconds. That limit was about 200° in 2 seconds. Pilots A and B indicated 3° bank in 2 seconds to be virtually uncontrollable.

Bank-angle changes in the first second of 22° to 24° were determined from these tests to be optimum (fig. 35), with a pilot rating of 2.5. Minimum bank angles of 8° to 10° in a second were required for a satisfactory rating, and 2° to 4° bank-angle changes in a second were necessary for a rating of 6.5 or better.

Reference 12 considered the roll requirements of a large transport airplane in normal roll maneuvers and during sidesteps performed during the approach to landing. Control sensitivity and power, roll time constant, and system lag were considered, and during a ground simulation program the effect of turbulence was studied. A roll criterion was developed in terms of bank-angle change in 1 second. Although the present results are for up-and-away flight, they are compared with the reference 12 results in figure 35. During the referenced tests, relatively small bank-angle changes in a second were rated somewhat better (lower rating number) for the approach task than were similar response characteristics during the present tests for up-and-away flight. The referenced results were a part of a study which indicated that pilot opinion could be maintained with a reduction in bank-angle response in a second if control sensitivity were maintained. Control sensitivity during the present tests varied as overall roll-control power and damping varied. For the more demanding approach and landing task of reference 12, it appears that control sensitivity was the important parameter, whereas, for normal roll maneuvering, roll-control power was more important.

The DC-8 subsonic jet transport is reported (ref. 13) to have a roll-stabilization capability of 6.5° of bank-angle change in 1 second, and that roll response has been rated "good" by pilots. The DC-8 data generally agree (fig. 35) with the present results, in which 8° to 10° of bank in a second were rated satisfactory by the three pilots.

The results of the present study are in general agreement with the conclusions of reference 4 that a bank-angle change of 30° in 2 seconds will be satisfactory. Time to bank or bank-angle change in a specified time provides effective criteria for the roll response of transport airplanes in cruise. Consideration of a more definitive roll task will be required if more specific criteria are to be developed.

Wheel force gradients. - The roll-control wheel force gradient was constant for most of the present tests, but the wide range of roll-response capability considered resulted in the coverage of a wide range of control sensitivities. The optimum roll-control sensitivities for pilot B (fig. 36) were determined by the previously described procedure. A bank-angle change in the first second per degree of wheel deflection of about 0.4, or per pound of wheel force of 1.0 (0.22 deg/N), was determined to be optimum by the three program pilots for the range of these tests (fig. 37). A wide range of control sensitivity of approximately 0.1° to 0.8° in the first second per degree of control-wheel deflection was determined to be satisfactory. The results showed an even greater range that would be acceptable but unsatisfactory. For the approach task investigated in reference 12, a $\frac{\varphi_1}{\delta_w}$ of 0.07 to 0.30 was rated satisfactory. The referenced tests also indicated that very low control sensitivities of approximately 0.03 deg/deg would be acceptable but unsatisfactory. These results are in general agreement with the present results, although the pilot ratings for the present results give a lower rating (larger number) than the referenced results for the comparable low roll sensitivity. Also, the referenced results covered only about a third of the range of the present tests and were for landing-approach conditions rather than cruising flight.

Since the GPAS had a variable-feel system for the simulation pilots, one flight was made allowing pilots A and C to select the most desirable force gradient for each of three flight conditions. The results from this flight, for wheel-force gradients of 0.2 to 0.6 lb/deg (0.9 to 2.7 N/deg) are presented in figure 38(a). These results may be compared with the average pilot ratings for pilots A and C and the average for all the pilots presented in figure 38(b) for the program force gradient of 0.4 lb/deg (1.8 N/deg). As can be seen, the force gradients selected were within the range tested (fig. 38(b)), and the pilot ratings were only improved by one rating number or less over the averages of the pilot ratings previously given by pilots A and C and all the pilots. Therefore, it may be concluded that, although the wheel force gradient used for the program drew comment (table 3, question J), the gradient was generally satisfactory. The comments of pilot A concerning the force gradients are summarized in appendix E.

General Roll-Criteria Comparisons

The roll-criteria results of the present study are presented in figure 39 for comparison with the results of other proposed criteria. Roll response has usually (ref. 1, for example) been defined by the roll-control angular-acceleration capability or steady-state roll rate and the roll time constant. These parameters are logical choices, for they completely define the airplane's uncoupled roll response.

Bisgood summarized the handling-qualities literature in reference 6. His recommendation for a roll criterion for transport airplanes in the approach configuration is shown in figure 39(a). Although maximum roll acceleration is used as the ordinate, the criterion is also presented in terms of roll rate, since lines of constant roll rate are lines of constant slope of $L_{\delta_a}\delta_{a_{max}}$ versus τ_R. The criterion suggests maximum roll rates of 60 deg/sec and minimums of 12 deg/sec for satisfactory roll maneuvering for transports. This region is bounded by a time constant of 2.7 seconds. The present test results indicate that somewhat greater roll capability is required for a satisfactory rating ($\leqq 3.5$). The steady-state roll-rate capability of about 17 deg/sec to 120 deg/sec was indicated for a satisfactory pilot rating, with a time constant of 1.8 seconds terminating the region. The two proposed criteria are in fair agreement on the unsatisfactory boundary for low control power. However, the present results indicate low roll damping to be more acceptable than indicated by the referenced study, and high roll-control power at high time constants was rated much more acceptable by pilots in the present study than was predicted by the Bisgood study. The present program pilots were critical of low control power but accepted very poor damping and very effective controls. The proposed criteria show similar trends, even though the referenced study considered landing approach and the present study was for cruising flight. It might be expected that lower roll rates would be acceptable for approach than for up-and-away maneuvering.

The methods of reference 2 can be used to predict the pilot rating of lateral-directional characteristics for several types of airplanes. The results of the present investigation and of reference 2 are compared in figure 39(b). Only two levels of roll-control power were directly applicable for the comparison with the present data, although a wide range of comparison data could be computed. The agreement of the prediction of pilot ratings from the two investigations is fairly good except at the highest control power and time constant, where the referenced study optimistically predicts a pilot rating of 3.5. Overcontrol tendency that might result from airplane motion would not be apparent on the fixed-base simulator used in the referenced study, so controls would not be as sensitive as in actual flight.

The criterion developed for steady-state roll rate (fig. 29) is compared with the Society of Automotive Engineer's Aerospace Recommended Practice (ref. 17) proposed criteria for civil transports in figure 39(c). The referenced criterion proposes only acceptable and unacceptable regions of steady-state roll rate as a function of steady-state roll rate and roll time constant. The minimum acceptable steady-state roll rate at low time constant proposed by reference 17 was 15 deg/sec, which is in good agreement with the lower roll-rate boundary for satisfactory pilot ratings determined from this study. The derived boundaries are, in general, similar; however, the referenced proposal allowed longer time constants than were satisfactory, according to the present results. The referenced boundary was within the acceptable but unsatisfactory boundary of this study.

Reference 17 suggests that the time constant for takeoff and landing configurations be limited to 1.5 seconds, which agrees with the limits of the criterion proposed by the present study for the satisfactory region.

The results of the present study and proposed roll criteria for both up-and-away flight and approach conditions are in general agreement.

Summary of Ground-Based Pilot Evaluations

During the preparation for the flight program, the three principal program pilots evaluated typical conditions and gave pilot ratings using the general purpose airborne simulator as a fixed-base simulator on the ground. The roll controls and model-controlled system operated as they did in flight. The cockpit displays were driven by the analog computers which solved a five-degree-of-freedom mechanization representing the JetStar flight dynamics. Figure 40 summarizes the pilot ratings obtained. As shown, the poor (high numbers) ratings dominate the low control power and long time constant boundaries, and the high control power and short time constant region was rated satisfactory. Cross-plotting these data provided guidelines for fairing the regions shown in figure 41. The satisfactory region is similar to that derived from the flight data. Although the unsatisfactory region appears to be contracted compared to that determined in flight, there is general agreement.

The ground-based pilot-rating data for a given flight condition were averaged, since the data were limited for comparison with the flight data. Ground and flight sample means are compared in table 4 and figure 42. The agreement was good at the satisfactory and the unacceptable levels of the pilot-rating scale. There was more variance in both ground and flight rating data in the unsatisfactory range. The range of pilot ratings for flight with a much larger sample of data was somewhat smaller than the range of data from the ground-based evaluations.

The linear regression line for the ground-derived data agrees well with the line of agreement for the flight data. Only at the satisfactory end of the pilot-rating scale was a pessimistic deviation apparent, and the deviation was only about one-half rating number.

From these data it appears that valid single-degree-of-freedom roll-evaluation results can be obtained by experienced pilots using fixed-base simulations.

CONCLUDING REMARKS

As a result of an in-flight simulation program which made it possible for pilots to evaluate and rate a wide range of roll-control power and roll time constant, roll criteria were developed for transport airplanes in cruise flight.

Short roll time constants (high damping) were appreciated by the pilots; however, maneuvering at low roll rates could be accomplished with very low levels of damping with increased pilot attention and compensation.

Roll-control power desired for satisfactory roll control decreased with increasing roll time constant. Increased steady-state roll rate with longer time constant was also desired by the pilots.

Although the wheel force gradient desired varies from pilot to pilot, probably strongly influenced by pilot experience, it appears that a wide range of wheel force and displacement is satisfactory. Large rotational displacements of the wheel required for low roll-control power were unsatisfactory, and the associated control forces were higher than desired. Also, the very effective levels of roll-rate response resulted in control displacements that were too sensitive for precise control and tended toward pilot-induced-oscillation conditions.

Pilot word responses to a well-designed questionnaire were effective in developing roll criteria.

Roll criteria based on maximum roll-control angular acceleration and roll time constant, maximum available roll rate and roll time constant, roll time constant, and bank-angle change in a given time all appeared to be effective.

Roll criteria developed in this study for up-and-away flight agreed well with a criterion developed by Bisgood for landing-approach conditions.

A steady-state roll rate of 15 to 20 deg/sec and roll time constants of 1.8 seconds or less were required for acceptable and satisfactory pilot ratings. Optimum pilot ratings were obtained for a roll capability of about 40 deg/sec with a time constant of 0.3 to 0.4 second.

Optimum pilot ratings were given for time to bank 30° of 1.5 seconds. Maximum times of 2.0 to 2.5 seconds were rated satisfactory. Also, a minimum bank-angle change in the first second of 8° to 10° was evaluated to be satisfactory.

The results also showed that pilot rating was relatively insensitive to the variation of bank-angle change in a second per unit of wheel travel. A value of 0.4 was rated to be the most satisfactory.

Flight Research Center,
National Aeronautics and Space Administration,
Edwards, Calif., April 24, 1970.

APPENDIX A

EXPERIMENTAL-DATA MEASUREMENTS

The same model-controlled system gains were used throughout the program and were a compromise for acceptable model following without being susceptible to noise and turbulence. The gains used proved to be satisfactory during the GPAS validation study. Very high gains would have been required for improved following at the short time constants and at the long time constants to keep the threshold of response low. Model following was acceptable, as shown previously.

The model and JetStar responses to step aileron commands were recorded prior to each pilot evaluation to obtain a record of the condition actually evaluated and the model following of the airplane. When possible, the airplane response was allowed to reach a steady-state roll rate, a time of at least three time constants. If not possible, the steady-state roll rate was solved for by using the experimentally measured roll rate and an assumed time constant. The time constant was then measured at the roll rate equivalent to 0.632 times the steady-state roll rate. The solution was repeated as necessary to improve the estimate of the time constant and steady-state roll rate. Time delays were not considered to be a part of the time constant in analyzing the experimental data. Means and standard deviations for the tabulated values of time constant and roll-control power simulated are presented in table 5 for comparison with the values set into the computer. The experimentally measured means for the model and the airplane responses are also compared.

The difference between the set values and the measured model means, with consideration for the standard deviations, indicates the accuracy expected of the method of analysis and the data recorded. The differences between the experimentally measured model and GPAS airplane data are attributable to inexact following of the model by the GPAS, the technique used to analyze the data, and the JetStar response to the flight environment of very light turbulence, which did not affect pilot ratings but did affect airplane response for checkout.

The check of the control power required the steady-state roll rate for an aileron step and the measured time constant. Inexact following of the first-order model was most noticeable at the very short time constants, shorter than the natural roll time constant of the JetStar. The JetStar did respond, with only short delay times, but the response was not first order. The pilots did not detect the system's delay as a delay and did not recognize the response as being other than first order.

The determination of the steady-state roll rate at the long time constants was difficult also. Accurate determination of steady-state roll rate required a record of at least three time constants in length. This was not always possible at the long time constants because of the bank-angle limitation of 60° for the GPAS. Low roll-rate response was selected in an attempt to obtain the desired record length, but the low roll rates resulted in the measurement being in the range of the recording and measuring accuracy and in the range of light turbulence encountered in some flights.

Reviewing the data obtained, the measured model and GPAS airplane time constant means agreed closely with the set values (table 5), except that the shorter

GPAS time constants were determined to be somewhat longer than the set values. Standard deviations were about 10 percent of the measured values, except at the shorter time constants where airplane following was less exact. The deviation of the model measures about the mean was about 50 percent less than those for the airplane (except those at τ_R = 10 seconds, which were about the same), indicating that the inaccuracy of measurement accounted for about half of the spread in the measured time constants for the GPAS and inexact following accounted for the remaining 50 percent of the spread.

By the method of analysis used, the variance in measuring the time constant caused variance in the values of roll-control power. The measured control power for the model response was consistent and was comparable to the set values in most instances. The control power measured for the GPAS showed poorer agreement with the set values and, in some instances, greater standard deviations about the means. Some difference in means and standard deviations was expected, considering the simple checks and methods of analysis used. GPAS following of the model was acceptable when compared to precomputed cases (a matter of judgment, of course). The pilots indicated that the conditions evaluated were similar to conditions encountered in actual flight. No effect of the very light turbulence on pilot evaluation was reported; however, some checkouts were repeated and light turbulence invalidated some check cases. Further analysis of the data obtained during the program indicated that the use of the experimentally measured response quantities would not alter the pilot-rating contours, particularly if pilot-rating variability were considered.

APPENDIX B

TYPICAL PILOT COMMENTS

The pilots commented on airplane handling, using the questionnaire given in table 1 as a guide. Selected comments, typical of the many recorded, are presented in this appendix. All the pilot comments are summarized in table 3.

Pilot A

$\underline{L_{\delta_a}\delta_{a_{max}} = 3.5 \text{ radians/second}^2, \tau_R = 0.1 \text{ second.}}$ —Ability to hold wings level was very good. Ability to roll to and stop at a desired bank angle slow and fast was good. Ability to make heading changes was OK. Control rate was acceptable. Full wheel could be used and was used on the roll reversal. Roll damping was very high. It was the first time I've seen roll damping that I'd say was too high. No tendency to P.I.O. [pilot-induced oscillation]. There was just a shade of delay between the wheel and the response; not too much. No special techniques were required; although, with the high damping, you had to turn almost to the heading, or hold the bank angle almost to the heading, before you released it. There was no lead required due to the very high damping. The control-wheel characteristics were acceptable. The controls were compatible with the aircraft response. It could be maneuvered OK with one hand. The control sensitivity was good. It was more like what I would expect on a transport, and, if it was on any side of optimum, I would say it was just a little low. The rating would be acceptable and satisfactory. I could not give it a 2; about a 3. The major complaints were just a little bit low on the sensitivity and just a little high on damping. Maybe a change in either one would improve it up to a 2. Doesn't seem like it would take too much. We'll call it a 3.

$\underline{L_{\delta_a}\delta_{a_{max}} = 0.2 \text{ radian/second}^2, \tau_R = 5.0 \text{ seconds.}}$ – The ability to hold wings level, not good. Ability to roll to and stop at a bank angle, not good, slow or fast. Ability to make heading changes follows, not so good. Control rate available, not so good; will talk about it later. All the roll rate or full wheel could be used, but that wasn't so easy either. The apparent damping was zero. It seemed like it was near divergent. If you stopped an input, the thing would continue or even increase in roll rate. The tendency was there to P.I.O. or overcontrol. It did oscillate a bit. There was a very noticeable lag between wheel and airplane response. It looked like a very nonlinear control. Just looked like it took a long time for the rate to develop; then, as it developed, it sort of continued to pick up and pick up for a given wheel input. You had to be careful and take out everything you put in with this condition, but you really couldn't help it too much. Yes, just barely acceptable on the control-wheel force and deflection. The controls were not compatible with aircraft response. It was mostly a phasing problem. Seemed like I was just out of phase and tended to P.I.O. it. It could not be maneuvered comfortably with one hand, but that wasn't due so much to the force. It was more due to the characteristics. The characteristics are unacceptable for a transport. Call it a U-7. The additional comments: The available response—if you wait long enough, you could develop a roll rate; however, it took so much time and got you out of phase so much that it was really difficult.

APPENDIX B

Pilot B

$L_{\delta_a}\delta_{a_{max}} = 0.1$ radian/second^2, $\tau_R = 10$ seconds. – That particular one has kind of an accelerating rate. Initially it was low, but as it picked up it gave me the rate that I wanted. It was not a very good flying machine and had extremely poor roll damping. Ability to hold the wings level was barely acceptable; you have to work at it. You can hold the wings level. The ability to roll and stop was not very good, particularly on a fast roll. The airplane has such poor roll damping that it takes a lot of anticipation to roll out exactly as you desire. Even on a slow rate or normal maneuver, it is still difficult to roll out as you desire. The same thing is true on the heading; it requires a little bit of anticipation and sometimes a sort of stepping to the desired heading. I suppose the maximum rate available is acceptable for a transport, but the way the roll rate comes on is not acceptable. It seems that if you put in a large input the initial roll velocity is very slow. The airplane seems to accelerate in roll velocity. It gets up to an acceptable rolling velocity, but the way it gets there is not acceptable. You can use full wheel throw, but, if you leave it in very long, the increasing roll velocity and the lack of roll damping cause the airplane to go easily to greater bank angle than you desire. As an example, rolling 30° left to 30° right, I put in full wheel and, at approximately 10° bank angle, I would come in with essentially full wheel throw again and the airplane would roll out near the 30° bank. So it requires quite a bit of anticipation and lead to roll out where you like. The roll damping is not acceptable; it is extremely low. The rolling velocity seems to increase when you release the wheel. There was no P. I. O. It required a lot of effort and anticipation. I'm not sure that there was an objectionable lag. It is not the true lag; you seem to get response right away, but the response is slow, so I suppose there is lag in getting the desired response, but there is no lag in getting some response. Special piloting technique: You must anticipate the lack of roll damping and the fact that the rolling velocity increases as the control input is held. Control-wheel-force characteristics are too much force to get the initial airplane response, and of course then you have to take the force out immediately or you get too much response. It is the same thing with the control wheel. The wheel and force tie right together there. You cannot maneuver with one hand, and it is quite a work load to anticipate the roll out and roll in with the high forces that are required to get the initial response and the high forces in the other direction to stop the airplane rolling velocity. Overall characteristics are not acceptable. Improvement: Increase the roll damping and then increase the onset of roll damping. I'm not sure whether you would want to increase the maximum velocity or not. It seems like the rate could be acceptable, but it is hard to evaluate this the way it responds. Rating, 7.5.

$L_{\delta_a}\delta_{a_{max}} = 2.0$ radians/second^2, $\tau_R = 0.35$ second. – Pretty good flying machine, really. It could use a couple improvements, but it wasn't really too bad. Ability to hold the wings level was good. Ability to roll to and stop at desired bank angle either fast or slow was excellent. The ability to make heading changes was satisfactory. Control rate available was acceptable. It could be slightly improved, but it was very good. All the full wheel could be used. Roll damping was quite good. There was no tendency to overcontrol or P. I. O. No objectionable lag between wheel and response. It seemed to be quite good. No special piloting technique was required. I think the techniques that we normally use were certainly acceptable. Control-wheel deflection and force characteristics were acceptable. Controls were compatible with the airplane response. You can maneuver comfortably and safely with one hand. Overall roll characteristics are acceptable for a transport. Any improvement made would be to decrease the force gradient very slightly and increase the roll rate very slightly.

Neither of these needs any large improvement, but they could use just a little bit. I would say that roll damping was adequate as is. Generally, a pretty good machine. Rating, 2.5.

$\underline{L_{\delta_a}\delta_{a_{max}} = 0.1 \text{ radian/second}^2, \ \tau_R = 0.35 \text{ second.}}$ – That was not a good flying machine; it does not have any roll power at all. The ability to hold wings level was excellent; you can hardly get it over into a bank. There was no fast rate; it does not have that much roll power. Slow is much too slow, but you certainly could roll to and stop at a desired bank angle; but it may take half a day to do it. As for making heading changes, I guess you'd have to say it is not acceptable because you could not get it over in time to make a heading change. It was certainly easy enough to roll out on any heading that you wanted, once you get it over into a bank, but it takes too long to get it into a bank. Roll rate is unacceptable for a transport. You can use full wheel throw. You use full wheel throw even to get a slow turn. Roll damping is very high—appears to be so high you can't get enough roll velocity to tell very much. It appears to be very good. No P. I. O. No objectionable lag, but the total response is objectionable. It does seem to respond to wheel inputs. Special piloting technique: You must anticipate that you have such low roll power that you make your turns ahead of time. The control deflection and force compatibility with airplane response was not good. Too much force and wheel throw was required to get any response. There was no one-hand operation. Can't be maneuvered safely with both hands; not enough roll power. Overall characteristics are not acceptable. Improvement: It must have increased roll rate. Roll damping seemed to be good. When you increase the roll rate, you would decrease the forces and deflection required to give the desired response. Rating, 9.0. It is only better than a 10 because a 10 is uncontrollable and you do have some control.

$\underline{L_{\delta_a}\delta_{a_{max}} = 3.5 \text{ radians/second}^2, \ \tau_R = 1.0 \text{ second.}}$ – It has extremely high roll sensitivity. The ability to hold wings level was acceptable, but it doesn't require much wheel travel or force. Ability to roll and stop at a bank was acceptable slow, but fast was not acceptable at all. You have too much roll rate; it is very easy to overshoot the desired bank angle. The same thing is true about heading changes; if you are making a moderately slow turn rate, then I think you can roll out reasonably well, but if you are trying to make a fast turn, then the control is such that you either roll out too quickly or not quickly enough. So it is not too good there. Roll rate available is not acceptable for a transport; it is much too sensitive; too much roll authority. All the wheel throw cannot be used. In fact, you can't even use two-thirds of it. The roll damping is marginally acceptable. It's not real strong, yet it's better than some we've looked at. There is a very slight tendency to overcontrol or P. I. O.; not very strong, but it is detectable. There was no lag. In fact, the response is very rapid. Special piloting technique requires that you be aware and fly in a manner not to use large wheel deflections or high forces because the airplane response is so high. The wheel force and deflection are not acceptable. The forces required to get response are much too low for the response. Same thing is true with the control deflection. It does not require very much control movement to get the large airplane response. It can be maneuvered comfortably with one hand, but certainly not safely, I don't think. Well, maybe safely also, but it is somewhat like the one we looked at before. If you were on instruments, you might have a tendency to overcontrol and maybe you would find it was not safe, but, as long as you kept your deflections and forces low, you'd probably find that it could be done with one hand. The overall characteristics are unacceptable for a transport. Improvements recommended: Decrease the roll rate by a substantial amount for large wheel input and increase the roll damping some. Rating: unacceptable, 7.

APPENDIX B

Pilot C

$L_{\delta_a}\delta_{a_{max}} = 0.5$ radian/second^2, $\tau_R = 0.35$ second. – The ability to hold wings level was excellent. The ability to roll to and stop at a desired bank was real good slow. You couldn't get what I'd call fast roll rate for a transport. The control rate was low, about half that desired for a transport. Full wheel could be used; it had to be used for any decent rate. I noticed I was using 35° to 40° of wheel for even small heading changes, which is more than you would want to do. Roll damping was beautiful. No P. I. O. tendency. No lag detectable between the wheel and response. No special technique was used. The control-wheel force and deflection were higher than I like. Forces and deflection or throw were high for moderate inputs for bank-angle changes. It was bordering on being two-handed when you want any degree of bank angle. For small changes, you could make it with one hand, but the force was higher than I like. Rating, 3.5. For improvements, increase the roll rate and decrease the wheel forces.

Pilot D

$L_{\delta_a}\delta_{a_{max}} = 0.5$ radian/second^2, $\tau_R = 10$ seconds. – For holding wings level, it didn't seem too bad flying straight and level; you could maintain wings level and you could maintain a bank angle. It seemed to build up, though, once you started a roll rate. It was surprisingly difficult to get the thing back to the desired bank angle. You could roll to and stop at a desired bank angle at a slow rate, but, at a fast rate, it seemed to build up as you went through the roll to the point where you would overshoot considerably. You could make heading changes at a slow roll rate. The control rate initially seemed acceptable for a transport, but after about 20° it was building up to the point where no matter what you did you were going to overshoot by a considerable amount. Full wheel could be used, but, here again, you would get the overshoot at the end of it. Roll damping was less than acceptable; well, not less than acceptable, less than desirable. It should be a little better damped. It would be better if it was. There is a tendency to overcontrol toward the end of the roll, and, once you realized that you were going to overshoot, you could put in opposite wheel and it was quite a delayed response to get your airplane started back in the other direction again. This would be somewhat objectionable, the lag between wheel and response in rolling out of a particular roll rate and stopping that roll rate. Special piloting technique is required to anticipate an overshoot. Control-wheel deflection and force characteristics seemed about right, although the response was sluggish in the end. The controls were compatible with response. Airplane could be maneuvered OK with one hand. Overall roll characteristics not acceptable as is, but wouldn't take much to improve on that. It is overly sensitive. The improvement would be to cut down this buildup in roll rate, increase the damping, and lower the maximum roll rate. Pilot rating: I would put it acceptable but unsatisfactory, about a 5.0 rating.

Pilot E

$L_{\delta_a}\delta_{a_{max}} = 1.0$ radian/second^2, $\tau_R = 1.0$ second. – I think this condition improved a little over the condition we just previously had. The ability to hold wings level is satisfactory. The ability to roll to and stop at a desired bank angle at a slow roll rate is good. At the fast rate there is a slight overshoot tendency. The ability to make heading changes is satisfactory. The control rate available is acceptable for a transport airplane. I'd say it's maybe on the high side. Again, I don't believe that I got into full wheel; I think maybe because the roll rates are a little bit higher than I would want to go to with full wheel. The roll damping is a little on the low side. It can be used the way it is, but I'd rather have more damping. Marginally acceptable, I'd say. There is a slight tendency to overcontrol or P.I.O., probably because of damping. No objectionable lag between the wheel and response; I wasn't particularly concerned with that. There are no special piloting techniques; however, you do have to anticipate the rollouts and pulse it in the opposite direction to stop it, but it isn't too bad in this configuration. The control-wheel deflection and force characteristics I think were acceptable. I think probably the controls were compatible with the airplane response. The force is a little bit on the light side, but I think it's OK. The airplane can be maneuvered comfortably and safely with one hand, at least in smooth air. There doesn't seem to be any big problem there. I think I would grade this approximately a 4.0. The improvements would be again in damping. I would like to see a little more damping in roll. It isn't what I would call a very bad configuration. I think it can be handled without too much trouble.

$L_{\delta_a}\delta_{a_{max}}$ = 2.0 radians/second^2, τ_R = 3.0 seconds.— This one, as you know by now, is a little touchy. The ability to hold wings level is degraded in this configuration and is very sensitive as far as wheel inputs are concerned. The ability to roll to and stop at a desired bank angle under a slow condition is satisfactory, but fast there is very definitely a tendency to overshoot. You can make heading changes without too much difficulty in smooth air with slow bank angles, slow rates of roll, but it becomes quite difficult at the higher rates because of overshoot tendencies. The control rate available is, I'd say, unacceptable from a transport standpoint because of the high rate of roll. I couldn't use what I'd call the full roll rate available. I didn't use full wheel, and we were considerably over what I would call the acceptable rates for a transport. Roll damping didn't seem to be there at all. It looks like it's neutrally damped to me. Very little damping, if there is some. There definitely is a tendency to overcontrol or P.I.O. when attempting to hold a bank angle or roll out wings level. No particular lag involved. It responds quite well to wheel input, and the airplane and the wheel seemed to be going together pretty good. The main thing as far as special techniques are concerned is the ability to lead it as far as going in and out of the turns because of its high rate capability. It's quite rapid. The control-wheel deflection and force characteristics are unacceptable, I'd say, for a transport because of the high sensitivity. It gives you too much roll for small deflections to the wheel. The controls, I think, are a little bit on the high side as far as being compatible with airplane response. For a given response, I'd much rather see a little more wheel deflection. The airplane can be maneuvered safely and comfortably with one hand; however, the roll rates had to be kept down, and this combination possibly in turbulence would give you a little trouble because of the high sensitivity on the wheel. The overall roll characteristics, I'd say, were not acceptable for a transport. I would put it around a 5.0 again. You can do the tasks at hand, but they are pretty sloppy. Requires you to stay on it pretty well. I would say that the areas I would improve would be mainly sensitivity. I think the sensitivity should be reduced a little, and I think the damping has to be improved. It's more typical of a fighter-type configuration, as far as roll response to wheel input is concerned.

APPENDIX C

PILOT VARIABILITY

Pilot ratings are subjective measures and so may have more variability than objective measures. Reference 15 discusses the use of pilot-rating scales and the conduct of experiments in which pilots are used. Careful program planning can reduce pilot variability. This appendix presents and discusses the pilot-rating variability obtained during the program.

It was recognized that pilot ratings may be influenced by such factors as the time in the program a test condition was introduced to the pilot and the test conditions immediately preceding an evaluation. Because it would be unrealistic to reevaluate all test conditions in all combinations of order, the test conditions were numbered and ordered from random number tables. Even so, some of the variability resulted from the order of test conditions evaluated. Pilot variability obtained during the program is presented in figures 43 to 48. Examples of intrapilot variability are illustrated in figure 43(a) for the three principal pilots in the program. Repeat evaluations were conducted as many as four times by pilot A and resulted in a range of pilot rating of 2 to 4.5. This, incidentally, was the range of pilot rating in evaluating the same condition twice during the same flight. This flight was the first flight on which permanent records were made for the program. Other examples resulted in less range of pilot ratings; however, the third example shown for pilot A also resulted in the same range. One of these test evaluations (rating of 2.5) was also early in the program (second flight for records). The later evaluation rating of 5.0 for the third test condition for pilot A was consistent with the other pilot ratings of that test condition. The pilots appeared to become more critical of airplane characteristics later in the program, especially poor damping.

The same test conditions were evaluated three times on different flights by each of the principal pilots in the program. The distribution of the intrapilot rating variation is shown in the top plot of figure 43(b). A larger sample of intrapilot variability was obtained for once-repeated evaluations by the pilots (lower plot). Although the intrapilot variability data had a mean of 0.8, the range of repeated evaluation rating numbers was 0 to 2.5. The standard deviation was also about 0.8 rating number. From this data it appears that a pilot can be expected to repeat evaluations with a rating within one rating number a high percentage of the time.

The differences in pilot ratings among the pilots are shown in figure 44. The range (fig. 44(a)) of pilot ratings in general appears to be slightly smaller at the lower pilot ratings, which indicates a satisfactory flight condition. The variability of the pilot rating in the midrange is about double that for the more satisfactory ratings, indicating less certainty as a group when the rating is unsatisfactory (from 3.5 to 6.5). Pilot-rating variability was lower again in the unacceptable rating range, indicating better agreement on the poorer pilot ratings.

The distribution of interpilot variability is summarized in figure 44(b). The mean difference between two pilot ratings was indicated to be somewhat less than one rating number, whereas with three pilots the mean difference was about 1.7 pilot-rating numbers.

The range of the differences in pilot rating with three pilots was also indicated to be large, since the standard deviation was about one rating number. These results include the effects of intrapilot variability, which, in some instances, represent a significant part of the range of pilot rating difference.

Ratings of each of the three primary evaluation pilots are compared with the average of all the pilot ratings in figures 45 to 47. Linear regression lines for the individual pilots were computed for comparison with the line of agreement for the average of the pilot ratings. Pilot A (fig. 45) was more optimistic at the satisfactory end of the rating scale and more pessimistic at the unacceptable end of the rating scale than the average rating of the pilots. Pilot B (fig. 46) was, in general, more pessimistic than the other pilots. His ratings were from a quarter to a half rating number higher (more unsatisfactory) than the average. Pilot C (fig. 47) was very optimistic at the conditions rated to be unacceptable. His ratings near the unacceptable rating end of the scale were as much as one rating number lower (more satisfactory) than the average of all the pilots. These trends are graphically illustrated in figure 48, which compares the three pilot linear regression lines and the line of agreement. The regression-line computation was based on the assumptions that the mean-square deviations of the individual pilot ratings were constant for all average pilot ratings and the regression curve was a straight line.

APPENDIX D

PILOT COMMENTS ON SELECTED ROLL-DAMPING CHARACTERISTICS

Pilot B

<u>Condition 1: $L_{\delta_a}\delta_{a_{max}}$ = 3.5 radians/second^2, τ_R = 0.35 second.</u> – I requested that the roll damping be increased about 50 percent above what it was originally set. I felt that the roll damping was increased to a satisfactory level, but I noticed that, as we increased the roll damping, we decreased the roll power slightly; in fact, it was probably more than just slightly. Prior to that change in the roll damping, the roll rate was such that I could not use full wheel; whereas, after the change in roll damping, I could put in full wheel throw.

Commenting on that condition as modified, using the questionnaire (table 1): A. – Good. B. – Both slow and fast, was good. The increase in roll damping allowed you to stop where you wanted even with a fast roll rate. C. – Good. Rate acceptable for a transport prior to the increase in damping. I would say that the roll rate was too high for a transport. All wheel throw could be used. Roll damping was acceptable. There was no P. I. O. or overcontrol tendency. There did not appear to be any objectionable lag. No special piloting technique was required. The control-wheel deflection and force characteristics were acceptable for a transport, although they were a little bit high. I would like a little less force and the same for wheel throw, slightly less. The airplane can be maneuvered comfortably and safely with one hand. The overall characteristics are acceptable for a transport. Improvements recommended would be to slightly decrease the wheel force and deflection, but primarily the wheel forces. Rating, 2.5.

Pilot A

<u>Condition 1: $L_{\delta_a}\delta_{a_{max}}$ = 2.0 radians/second^2, τ_R = 0.35 second.</u> – Initial roll authority and damping looked good. A 25-percent reduction in damping over the original was not obvious, but with a 50-percent change it became obvious to me that I would have given it a lower rating. I tried 50 percent higher since it took 50 percent lower to get a change, and at 50 percent higher it had obviously reduced the roll authority which I had liked originally. It was extremely stiff in damping, which isn't too bad, of course; high damping is not bad unless it reflects back into the roll authority in the authentic response of the airplane. I think it had an artificial response. It did not respond like an airplane or like good roll damping, so this was too high, so I returned to the original as being optimum for the roll power. Commenting on the questionnaire (table 1): A. – Good. B. – Slow and fast, good. That was one thing I looked at. C. – Good. Rate available definitely acceptable. Full wheel was acceptable. Roll damping was good, as already discussed. No P. I. O. No lag. No special techniques. Wheel deflection and force characteristics were acceptable. Controls were compatible and could be maneuvered with one hand. Overall, the airplane was acceptable and satisfactory. Rating, 2.0.

Condition 2: $L_{\delta_a}\delta_{a_{max}} = 1.0$ radian/second^2, $\tau_R = 1.0$ second. — The original roll authority was quite acceptable. The roll damping was too low; so we increased it 50, 75, and 100 percent before I noticed an obvious improvement in the damping at 100 percent. I also noticed between 75 and 100 percent a drop off in the roll response. It didn't drop it out of the acceptable area by any means, but because of this I went to 150-percent damping. I liked that best as far as aircraft damping in roll as I neutralized the control. I did not like the reduction in roll authority, so, picking the best balance, I went back to the 100 percent, and that damping was probably a bit on the low side. This condition was not quite as good a condition as before. Commenting again on the questionnaire (table 1): A. — Good. B. — Slow; the roll damping appeared quite adequate and on the fast rate it was a little bit lacking, which goes along with what I said before. C. — Good. Control rate was acceptable. Full control wheel could be used. No P. I. O. No lag. No special techniques. Control deflection and force characteristics were acceptable and compatible with airplane response. OK, one hand. Definitely acceptable and satisfactory. Rating, 3.0.

Condition 3: $L_{\delta_a}\delta_{a_{max}} = 3.5$ radians/second^2, $\tau_R = 0.35$ second. — Initially, the condition seemed to have high roll sensitivity and what I'd call moderate damping. Not really low, but on low side, and I called for an increase of 50 percent, which was an obvious change in damping. I went on to 100 percent and picked up the apparent degradation in roll authority. At 100 percent the damping was high, but it was not bothersome because it was high. It was not an artificial-feel airplane as reported on an earlier case; however, I did not like the reduction in roll response, so I went back to the 75-percent increase and decided that that would be the optimum condition.

Commenting on the questionnaire (table 1): A. — Good. B. — Slow and fast good. C. — Good. Control rate definitely acceptable. Used about 3/4 wheel, but I think I could have used all of it. It was not too sensitive to handle. Roll damping was acceptable after changes. No P. I. O., lag, or special techniques. Control deflection and force were acceptable and compatible with aircraft response. Could definitely be maneuvered with one hand, real nice feel system there, but would not want it any more sensitive. Acceptable, satisfactory. Rating, 1.5.

APPENDIX E

PILOT A COMMENTS ON THE SELECTION OF CONTROL-WHEEL FORCE GRADIENTS FOR THREE FLIGHT CONDITIONS

Condition 1: $L_{\delta_a}\delta_{a_{max}} = 0.5$ radian/second^2, $\tau_R = 1.0$ second.– The roll response is slightly on the low side. The damping could be a little bit higher. The damping is positive, but it's just a bit too light. A little bit of damping would improve this condition. Overall, it's really not too bad. It could be a transport type of condition. On the rating I'll call this unacceptable. I'll call it a 3.5 on the rating. It's between. It's really almost satisfactory, but it has several characteristics there that could be improved.

This is a more difficult evaluation task than we have been doing. I started out initially commenting that the roll power was a little bit low and the damping was low, even though it was, say, acceptable in that range. I went to 0.3 lb/deg on the wheel force gradient and it did improve this system as far as the pilot roll input; however, it seemed that more pilot damping was required, especially at the higher roll rates. So I went back to 0.5 lb/deg, and I found that, although the extra force was undesirable, the task of the pilot providing damping was reduced. These comments concern normal rolling maneuvers back and forth. The increased force attenuated the pilot where he wasn't required to put in so many counter inputs or damping inputs. At the 0.4 pound again, the one I started with originally, I don't think I saw that much improvement from going to either side, and I just assume that 0.2 and 0.6 would be just that much further away, so I'll go with the 0.4. After looking at the thing a little bit more, I'd call it up to a pilot rating of 3.0. I think I had called it 3.5 initially; I'll call it 3.0. It is in the satisfactory area.

Condition 2: $L_{\delta_a}\delta_{a_{max}} = 1.0$ radian/second^2, $\tau_R = 1.0$ second.– This one seems real good, laterally. It's a little bit low on damping. The response I like. Roll sensitivity, it's good for one hand or two hands; it's really good. The damping is positive, although it's a little bit low. I think I would request a little more damping if we're working in that area. The control feels pretty good. Rating-wise, I'll rate this one 2.0. A little bit more damping would make it even better. Now force-wise, I like the 0.4 lb/deg wheel force gradient, but I think I'll try 0.3 now.

I did rate it a 2.0 and felt that the roll response was good. The damping was a little bit low. I tried 0.3 lb/deg, and I noticed a degradation in the overall lateral control. I did not like 0.3 as well as 0.4. It was working me a little bit more on the damping. I was apparently tending to put in a little bit higher inputs. I then tried 0.5 lb/deg as an increase, and that was a small improvement over 0.4 but not enough to cause me to go from a rating of 2.0 to 1.5 or anything. I think if I had a choice I would probably take the 0.5 lb/deg. I'm a little hard-pressed to say really how much better than 0.4 it is; but it did seem to improve a little. I think that it's sort of helping me take it a little easier; I don't require as much damping input to the control. So I'll leave it at that. The damping is low; it remains at 2.0. At 0.5 lb/deg the little increase in wheel force was better than a decrease in the force feel.

Condition 3: $L_{\delta_a}\delta_{a_{max}} = 2.0$ radians/second^2, $\tau_R = 1.0$ second. – It's fairly sensitive in the response. The response is on the high side. On the damping, it's a little bit low on damping for the existing control sensitivity, so I do quite a bit of oscillating around the desired bank angles. If I have any rate at all, I find that I overshoot. I can do it OK for slow rolls and stops, but for any sort of a moderate roll or bank I tend to overshoot and go by, I think due to the sensitivity and damping combined. You can't often save it by just taking it a little bit easier. There's no tendency to sit and P. I. O. so much once you're there, maybe just a little bit, but it's more of an overshoot, reset type of situation. A quickie evaluation, it's acceptable. It's on the high side in sensitivity, low side on damping a little bit.

You do oscillate a bit about the desired bank angle. It is OK at slow roll rates, but for moderate roll rates you overshoot due to the poor damping. It is not really P. I. O.; it is overshoot or oscillating because of the high response, low damping. Pilot rating would be 3.0. The condition is fair, with some mildly unpleasant characteristics. Tried 0.6 lb/deg. The increased force gradient made a good improvement. It felt better. It did not have the oscillation problem previously noted. Tried 0.3 lb/deg wheel force gradient. That proved to be the wrong way to go; the lower force gradient increased the response sensitivity. At 0.6 lb/deg the increase in force feel helped compensate for the low damping. The pilot rating is 2.5 with the 0.6 lb/deg gradient.

REFERENCES

1. Creer, Brent Y.; Stewart, John D.; Merrick, Robert B.; and Drinkwater, Fred J. III: A Pilot Opinion Study of Lateral Control Requirements for Fighter-Type Aircraft. NASA Memo 1-29-59A, 1959.

2. Taylor, Lawrence W., Jr.; and Iliff, Kenneth W.: Fixed-Base Simulator Pilot Rating Surveys for Predicting Lateral-Directional Handling Qualities and Pilot Rating Variability. NASA TN D-5358, 1969.

3. Kelly, Henry J.; and Aubin, William M.: Mission Analysis to Determine Roll Performance Requirements. Res. Rep. RE-125, Grumman Aircraft Engineering Corp., Mar. 1960.

4. Ashkenas, I. L.: A Study of Conventional Airplane Handling Qualities Requirements. Part I. Roll Handling Qualities. Tech. Rep. AFFDL-TR-65-138, Air Force Flight Dynamics Lab., Wright-Patterson Air Force Base, Nov. 1965.

5. McLaughlin, Milton D.; and Whitten, James B.: Pilot Evaluation of Dynamic Stability Characteristics of a Supersonic Transport in Cruising Flight Using a Fixed-Base Simulator. NASA TN D-2436, 1964.

6. Bisgood, P. L.: A Review of Recent Handling Qualities Research, and Its Application to the Handling Problems of Large Aircraft. Royal Aircraft Establishment Rep. No. TN Aero 2688, Brit. R.A.E., June 1964.

7. Leyman, C.; and Nuttall, E. R.: A Survey of Aircraft Handling Criteria. C. P. No. 833, British A.R.C., 1966.

8. Chalk, C. R.; and Wilson, R. K.: Airplane Flying Qualities Specification Revision. Paper No. 68-245, AIAA, Mar. 1968.

9. Chalk, C. R.; Neal, T. P.; Harris, T. M.; Pritchard, F. E.; and Woodcock, R. J.: Background Information and User Guide for MIL-F-8785B(ASG), "Military Specification - Flying Qualities of Piloted Airplanes." Tech. Rep. AFFDL-TR-69-72, Air Force Flight Dynamics Lab., Wright-Patterson Air Force Base, Aug. 1969.

10. Patterson, G. A.; and Spangenberg, W.: The Provision of Adequate Lateral Control Power for Landing Approach Conditions. AGARD Rep. 419, Jan. 1963.

11. Rhoads, Donald W.: In-flight Simulation and Pilot Evaluation of Selected Landing Approach Handling Qualities of a Large Logistics Transport Airplane. Tech. Rep. AFFDL-TR-67-51, Air Force Flight Dynamics Lab., Wright-Patterson Air Force Base, July 1967.

12. Condit, Philip M.; Kimbrel, Laddie G.; and Root, Robert G.: Inflight and Ground-Based Simulation of Handling Qualities of Very Large Airplanes in Landing Approach. Boeing Co. (NASA CR 635), 1966.

13. Drake, Douglas E.: Douglas Aircraft Company Experience With Current Military Airplane Flying Quality Requirements - MIL-F-8785. Flying Qualities Conference, Wright-Patterson Air Force Base, Ohio, 5 and 6 April 1966, Tech. Rep. AFFDL-TR-66-148, Air Force Flight Dynamics Lab., Wright-Patterson Air Force Base, Dec. 1966, pp. 59-68.

14. Clark, Daniel C.; and Kroll, John: General Purpose Airborne Simulator - Conceptual Design Report. Cornell Aeronautical Lab. (NASA CR 544), 1966.

15. Harper, Robert P., Jr.; and Cooper, George E.: A Revised Pilot Rating Scale for the Evaluation of Handling Qualities. AGARD C. P. No. 17, Stability and Control. Part 1, Sept. 1966, pp. 227-245.

16. Anon.: Flying Qualities of Piloted Airplanes. Military Specification MIL-F-008785B(ASG), Aug. 7, 1969.

17. Anon.: Design Objectives for Flying Qualities of Civil Transport Aircraft. Aerospace Recommended Practice (ARP) 842 SAE, Aug. 1, 1964.

TABLE 1.–PILOT QUESTIONNAIRE

Considering airplane roll response for passenger-carrying transports in cruise conditions, comment on each of the following:

A. Ability to hold wings level.

B. Ability to roll to and stop at desired bank angle slow, fast.

C. Ability to make heading changes.

D. Is control rate available acceptable for a transport?

E. Could all roll rate (full wheel) be used?

F. Was roll damping acceptable?

G. Any tendency to overcontrol or P. I. O. [pilot-induced oscillations]?

H. Was there objectionable lag between wheel and response?

I. Any special piloting technique required?

J. Were the control-wheel deflection and force characteristics acceptable for a transport?

K. Were the controls compatible with airplane response?

L. Can the airplane be maneuvered comfortably and safely with one hand?

M. Were the overall roll characteristics acceptable for a transport?

N. Any improvement recommended?

Demonstrate –

Normal roll rate for transport operation.

Fast roll rate, maximum normally used in transport operation.

TABLE 2. – COOPER-HARPER SCALE FOR PILOT RATING

CONTROLLABLE CAPABLE OF BEING CONTROLLED OR MANAGED IN CONTEXT OF MISSION, WITH [illegible]LE PILOT ATTENTION	ACCEPTABLE MAY HAVE DEFICIENCIES WHICH WARRANT IMPROVEMENT, BUT ADEQUATE FOR MISSION. PILOT COMPENSATION, IF REQUIRED TO ACHIEVE ACCEPTABLE PERFORMANCE, IS FEASIBLE.	SATISFACTORY MEETS ALL REQUIREMENTS AND EXPECTATIONS, GOOD ENOUGH WITHOUT IMPROVEMENT CLEARLY ADEQUATE FOR MISSION.	EXCELLENT, HIGHLY DESIRABLE	A1
			GOOD, PLEASANT, WELL BEHAVED	A2
			FAIR. SOME MILDLY UNPLEASANT CHARACTERISTICS. GOOD ENOUGH FOR MISSION WITHOUT IMPROVEMENT.	A3
		UNSATISFACTORY RELUCTANTLY ACCEPTABLE. DEFICIENCIES WHICH WARRANT IMPROVEMENT. PERFORMANCE ADEQUATE FOR MISSION WITH FEASIBLE PILOT COMPENSATION.	SOME MINOR BUT ANNOYING DEFICIENCIES. IMPROVEMENT IS REQUESTED. EFFECT ON PERFORMANCE IS EASILY COMPENSATED FOR BY PILOT.	A4
			MODERATELY OBJECTIONABLE DEFICIENCIES. IMPROVEMENT IS NEEDED. REASONABLE PERFORMANCE REQUIRES CONSIDERABLE PILOT COMPENSATION.	A5
			VERY OBJECTIONABLE DEFICIENCIES. MAJOR IMPROVEMENTS ARE NEEDED. REQUIRES BEST AVAILABLE PILOT COMPENSATION TO ACHIEVE ACCEPTABLE PERFORMANCE.	A6
	UNACCEPTABLE DEFICIENCIES WHICH REQUIRE MANDATORY IMPROVEMENT. INADEQUATE PERFORMANCE FOR MISSION EVEN WITH MAXIMUM FEASIBLE PILOT COMPENSATION.		MAJOR DEFICIENCIES WHICH REQUIRE MANDATORY IMPROVEMENT FOR ACCEPTANCE. CONTROLLABLE. PERFORMANCE INADEQUATE FOR MISSION, OR PILOT COMPENSATION REQUIRED FOR MINIMUM ACCEPTABLE PERFORMANCE IN MISSION IS TOO HIGH.	U7
			CONTROLLABLE WITH DIFFICULTY. REQUIRES SUBSTANTIAL PILOT SKILL AND ATTENTION TO RETAIN CONTROL AND CONTINUE MISSION.	U8
			MARGINALLY CONTROLLABLE IN MISSION. REQUIRES MAXIMUM AVAILABLE PILOT SKILL AND ATTENTION TO RETAIN CONTROL.	U9
UNCONTROLLABLE CONTROL WILL BE LOST DURING SOME PORTION OF MISSION.			UNCONTROLLABLE IN MISSION.	10

TABLE 3. – SUMMARY OF PILOT

Test condition	$L_{\delta_a}\delta_{a_{max}}$, rad/sec^2	τ_R, sec	$(p_{ss})_{max}$, deg/sec	Pilot	Pilot rating	Question A	B	C	D	E	F
1	0.05	0.35	1.05	C	9	Excellent	Good, slow	Good	Not acceptable, too low	Yes	Good
2	.05	1.0	3.0	A	9.5	Good	Difficult	Difficult	Not acceptable, too low	Yes	Acceptable
3	.05	3.0	9.0	A	9	Bad	Bad	Bad	Not acceptable, too low	Yes, no help	Acceptable, low
4	.05	3.0	9.0	B	8.5	Good	Acceptable, slow	Acceptable	Not acceptable, too low	Yes	Not acceptable, too low
5	.05	10	30.0	A	8	Very poor	Very poor	Very poor	Not acceptable, too low	Yes	Not acceptable, very low
6	.05	10	30.0	B	7	Acceptable	Poor	Poor	Slightly low	Yes	Not acceptable, weak
7	.05	10	30.0	C	7	Poor	Poor	Poor	Not acceptable, low	Yes	Not acceptable, low
8	.1	.35	2.1	A	9	Very poor	Very poor	Very poor	Completely unacceptable	Yes, no help	Good
9	.1	.35	2.1	B	9	Excellent	Fair	Not acceptable	Not acceptable, too low	Yes	Very high
10	.1	.35	2.1	C	7	Good	Fair	Fair	Not acceptable, too low	Yes	Good
11	.1	1.0	6.0	A	8	Poor	Poor	Difficult	Too low	Yes	Good
12	.1	1.0	6.0	A	8	Poor	Poor	Poor	Not acceptable, slow is maximum	Yes	Good
13	.1	1.0	6.0	B	8	Good	Fair, slow	Acceptable	Not acceptable, too low	Yes	Acceptable
14	.1	1.0	6.0	C	5	Very good	Good, slow	Good	Not acceptable, too low	Yes	Acceptable
15	.1	3.0	18	A	8	Poor	Poor	Poor	Not acceptable	Yes	Very low
16	.1	3.0	18	B	6.5	Good	Acceptable	Acceptable	Not acceptable, too low	Yes	Not acceptable, too low
17	.1	3.0	18	C	5	Acceptable	Acceptable	Acceptable	Slow, too low	Yes	Too low
18	.1	5.0	30	A	5	Fair	Fair	------------	Acceptable, low	Yes	Low
19	.1	5.0	30	B	6	Good	Fair	Reasonable	Acceptable	Yes	Weak
20	.1	5.0	30	B	7	Good	Poor	Acceptable	Not acceptable	Yes	Very low
21	.1	10	60	A	7	----------	Poor	Poor	Not acceptable, too low	---	Marginal
22	.1	10	60	B	6	----------	Acceptable, slow	Acceptable	Acceptable, may be low	Yes	Low, very bad
23	.1	10	60	B	7.5	Poor	Poor	Poor	Fairly	Yes	Not acceptable, too low
24	.1	10	60	C	6	Good	Poor	Good	Acceptable	Yes	Not acceptable, too low
25	.2	.1	1.2	A	9.5	Poor	Poor	Poor	Not acceptable, too low	Yes, no help	Can't evaluate
26	.2	.1	1.2	B	9.25	Excellent	Fair	Not acceptable	Much too low	Yes	Very high
27	.2	.35	4.2	A	8	Good	Very poor	Difficult	Not acceptable, low	Yes	Good
28	.2	.35	4.2	A	8	Fair	Fair	Difficult	Not acceptable, low	Yes	Good
29	.2	.35	4.2	B	7	Excellent	Slow, excellent	Good	Not acceptable, low	Yes	Good
30	.2	.35	4.2	C	6	Good	Slow only	Good	Too low	Yes, more	Not best
31	.2	1.0	12	A	5.5	Good	Good slow	------------	Too low	Yes	Acceptable
32	.2	1.0	12	C	5	Real good	Real good	Real good	Not acceptable, low	Yes, must	Fair
33	.2	1.0	12	E	5	Good	Poor	Fair	Not acceptable, low	Yes	Acceptable
34	.2	3.0	36	A	2.5	----------	----------	Good	Acceptable	No	Low
35	.2	3.0	36	A	5	Fair	Fair	Fair	Acceptable, low	Yes	Not acceptable, low
36	.2	3.0	36	B	5	Acceptable	Fair	Acceptable	Acceptable	Yes	Not acceptable, too low
37	.2	3.0	36	B	5	Good	Acceptable, slow	Acceptable	Acceptable	Yes	Not acceptable, low
38	.2	3.0	36	B	5.5	Acceptable	Fair	Acceptable	Acceptable, slightly low	Yes	Not acceptable, low
39	.2	3.0	36	C	5	Very good	----------	Fair	Low	Yes	Not acceptable, low
40	.2	5.0	60	A	7	Poor	Poor	Poor	Acceptable-slow build-up	Not easy, yes	Not acceptable, zero
41	.2	5.0	60	B	7	Acceptable	Marginal	Marginal	Not acceptable, low	Yes	Not acceptable, low

COMMENT DATA

(table 1)

G	H	I	J	K	L	M	N
No	------	No	Force and deflection high	No	No	Not acceptable	Increase roll response
No	Yes	No	Force too high	No	No	Not acceptable	Increase roll rate
No	Yes	No usable technique	No	No	No	Not acceptable	Increase response and damping
No	Slight	Anticipate roll	Not acceptable, too high	No	Not comfortable	Not acceptable	Increase roll power and damping, decrease lag
No	Low response	Large inputs	Not acceptable, force high	No	No	Not acceptable	Increase response and damping
No	No	Anticipate roll	Deflection and force too high	No	No	Not acceptable	Increase roll rate and damping
No	No	Anticipate roll	Wheel forces high	No	No	Not acceptable	Increase roll power and damping
No	------	No	Not acceptable	No	No	Not acceptable	Greatly increase response
No	No	Anticipate slow response	Not acceptable, high forces	No	No	Not acceptable	Increase roll power
----	No	No	Forces too high	No	No	Not acceptable	Increase roll rate, decrease forces
No	No	No	Deflection and force too high	No	No	Not acceptable	Increase roll response
No	Slight	No	Forces too high	No	No	Not acceptable	Increase roll rate
No	Slight	Large controls	Force too high	No	No	Not acceptable	Increase response, decrease force and deflection
No	No	No	Force and deflection high	No	No	Not acceptable	Increase roll rate
Yes	Yes	Provide damping	Barely acceptable	No	No	Not acceptable	Increase damping
No	Slight	Use lots of wheel	Forces high, not acceptable	No	No	Not acceptable	Increase roll rate and damping
No	No	------------	Forces high	No	No	Acceptable, unsatisfactory	Double roll rate
No	Yes	Counter inputs	----------------	No	------	Acceptable, unsatisfactory	Increase damping
No	Definitely	Anticipate lag	Acceptable, high forces	OK	Yes	Barely acceptable	Cut lag, increase damping and roll rate
Slight	Definitely	Anticipate lag	Force heavy	No	No	Not acceptable	Increase roll rate damping
Yes	Yes	No	Forces high	No	No	Not acceptable	Increase roll rate
No	Slight	Anticipate roll	Too high	No, too much δ_w	No	Not acceptable	Increase roll rate and damping
No	No	Anticipate roll	Force much too high	No	No	Not acceptable	Increase roll damping
No	No	Anticipate roll	Acceptable	No	Yes	Not acceptable	Increase damping
No	No	No	Not acceptable, high force	No	Yes	Not acceptable	Large, increase response
No	No	Anticipate slow response	Force too high	No	No	Not acceptable	Increase roll power
No	No	No	Forces too high	No	No	Not acceptable	Increase roll response
No	Not objectionable	No	Not acceptable, force high	No	No	Not acceptable	Increase roll rate
No	No	No	Not acceptable force-deflection high	------	No	Not acceptable	Large, increase roll rate
---	No	Large deflections	Wheel force high	No	No	Not acceptable	Increase rate, decrease forces
No	No	No	Forces high	No	No	Not acceptable	Increase roll rate
No	No	Use large deflection	Forces high	No	No	Not satisfactory	Increase available, decrease forces
No	Definitely	Lead inputs	Poor response	No	Yes	Not acceptable	Increase response
No	Slight	No	Acceptable	Yes	Yes	Acceptable	Increase roll damping
No	No	Provide damping	Response low	No	Not comfortable	Acceptable, unsatisfactory	Increase damping and response
No	No	Provide damping	Acceptable	No	Yes	Acceptable, unsatisfactory	Increase damping and rate slightly
No	Yes	Anticipate lag	Acceptable	Yes	Yes	Acceptable	Increase roll damping, cut lag
No	Slight	Anticipate roll	Not acceptable, too high	No	Yes-work	Acceptable unsatisfactory	Increase roll damping and rate slightly
No	Slight	Provide damping	Acceptable	------	------	Marginal	Increase roll rate and damping
Yes	Yes	Provide damping	Barely acceptable	No	No	Not acceptable	Increase damping and rate
No	No	Anticipate roll	Forces too high	No	No	Not acceptable	Increase damping and roll rate

TABLE 3. – SUMMARY OF PILOT

Test condition	$L_{\delta_a}\delta_{a_{max}}$, rad/sec^2	τ_R, sec	$(p_{ss})_{max}$, deg/sec	Pilot	Pilot rating	Question					
						A	B	C	D	E	F
42	0.2	5.0	60	C	5	Fair	Fair	Good	Acceptable	No	Much too low
43	.2	10	120	A	6	Fair	Poor	Fair	Acceptable	Yes	Low
44	.2	10	120	B	7.5	Barely acceptable	Poor	Poor	After buildup, acceptable	Yes	Completely-not acceptable
45	.2	10	120	C	5	Fair	Fair	Fair	Too slow	Yes	Not acceptable, low
46	.5	.1	3	A	9	Poor	Very difficult	Difficult	Too low	Yes	OK, good
47	.5	.1	3	B	9	Good	Good, slow	Acceptable	Not acceptable, low	Yes	Acceptable
48	.5	.1	3	C	8	Good	Good	Fair	Too low	Yes	Acceptable
49	.5	.35	10.5	A	6	Average	Poor	Fair	Acceptable, low	Yes	Good
50	.5	.35	10.5	B	6	Very good	Very good	Good	Low, not acceptable	Yes	Very good
51	.5	.35	10.5	C	4	Very good	Good	------------	Slow, too low	Yes	Good
52	.5	.35	10.5	C	3.5	Excellent	Very good	Very good	Too low	Yes	Excellent
53	.5	.35	10.5	E	5	Good	Good	Fair	Low	Yes	Good
54	.5	1.0	30	A	2	Good	Good	Good	Acceptable	Yes	Very good
55	.5	1.0	30	A	2	----------	----------	------------	Acceptable	Yes	Good
56	.5	1.0	30	A	3.5	----------	----------	------------	Acceptable, low	-----	Acceptable, low
57	.5	1.0	30	B	2	Excellent	Very good	Good	Acceptable, slightly low	Yes	Acceptable
58	.5	1.0	30	B	3.5	Good	Good	Good	Acceptable	Yes	Acceptable
59	.5	1.0	30	C	3.5				Acceptable, bit low		Acceptable, low
60	.5	1.0	30	C	3	Good	Good	Good	Good, acceptable	Yes	Slightly low
61	.5	1.0	30	E	2.5	Good	Fair	Good	Acceptable	Could	Acceptable
62	.5	1.5	45	A	2.5	Good	Good	Good	Acceptable	Yes	Acceptable
63	.5	3.0	90	A	5	Poor	Poor	Poor	Acceptable	Not used	Not acceptable, low
64	.5	3.0	90	B	5	Acceptable	Fair	Fair	Acceptable	Yes	Not acceptable, low
65	.5	3.0	90	B	4.5	Acceptable	Acceptable	Acceptable	Acceptable	Yes	Weak
66	.5	3.0	90	C	4.5	Good	Marginal	Good	Acceptable	Yes	Too low
67	.5	3.0	90	E	5	Fair	Poor	Poor	Acceptable	No	Very poor
68	.5	10	300	A	3	Very good	Average	Good	Acceptable, slightly high	No	Low
69	.5	10	300	A	4.5	Poor	Fair	Good	Good	No	Not acceptable, very low
70	.5	10	300	B	6.5	Acceptable	Poor	Acceptable	Not acceptable, too high	No	Not acceptable, too low
71	.5	10	300	B	6	Acceptable	Fair	Acceptable	Acceptable, high	Yes	Not acceptable, too low
72	.5	10	300	C	7	Acceptable	Fair	Fair	Not acceptable, high	Yes	Much too low
73	.5	10	300	D	5	Poor	Fair	Fair	Acceptable	No	Acceptable, low
74	.5	10	300	D	5	Fair	Fair	Fair	Acceptable	Yes	Low
75	1.0	.1	6	A	7	Good	Fair	Average	Much too low	Yes	Good
76	1.0	.1	6	B	7	Good	Good	Good	Too low, one-half desired	Yes	Good
77	1.0	.1	6	C	5	Very good	Good	------------	Slow, too low	Yes	Good
78	1.0	.35	21	A	4	Good	Reasonable	Good	Acceptable, low	Yes	Acceptable, high
79	1.0	.35	21	B	4	Good	Very good	Good	Barely acceptable	Yes	Very high
80	1.0	.35	21	C	2	Real fine	Fine	Fine	Acceptable	Yes	Very fine
81	1.0	.35	21	D	2.5	Good	Good	Good	Acceptable	Yes	Good
82	1.0	1.0	60	A	1.5	Very good	Very good	Very good	Very good	Yes	Good
83	1.0	1.0	60	A	2.5	Good	Good	Good	Good	Could	Low
84	1.0	1.0	60	A	2	----------	----------	------------	Acceptable, very good	-----	Acceptable, slightly low

COMMENT DATA - Continued

(table 1)

G	H	I	J	K	L	M	N
No	------	Anticipate roll	Yes, about right	------	------	Not acceptable	Increase damping and response
Yes	Yes	No	Acceptable	No phase controls	No	Acceptable, unsatisfactory	Increase roll damping
No	Slight	Anticipate roll	Not acceptable	No	No	Not acceptable	Increase damping and response, cut lag
No	No	Anticipate roll	----------------	------	No	Marginal	Increase roll response and damping
No	Yes	No	Deflection and force too high	No	No	Not acceptable	Increase response greatly
No	No	Anticipate low response	Not acceptable	High force	No	Not acceptable	Increase roll rate
No	Slight	No	Forces too high	No	No	Not acceptable	Increase roll rate
No	No	No	Not quite acceptable	No	No	Low rate, marginal	Increase roll rate
No	No	Use lots of wheel	Too much wheel required	Large, no deflection and force	Yes	Not acceptable	Increase roll rate
No	No	No	Wheel forces high	No	Yes	Marginally acceptable	Double roll rate
No	No	No	Force and deflection high	------	No	Not acceptable	Roll rate one-half desired
No	Definitely	Lead inputs	Force high	Low response	Yes	Not acceptable	Increase roll response
No	No	No	Good	Yes	Yes	Acceptable, good	
No	No	No	Reasonable	Yes	Yes	Acceptable	
---	------	------	----------------	------	------	Acceptable	
No	No	No	Acceptable, force slightly high	Yes	Yes	Acceptable	Increase rate and damping slightly
No	No	No	Acceptable	Yes	Yes	Acceptable	Decrease force, increase roll rate
						Acceptable	
No	No	No	Yes	Yes	Yes	Acceptable	Increase damping
No	No	No	Acceptable	Yes	Yes	Acceptable	Cut roll sensitivity
No	No	No	Acceptable	Yes	Yes	Acceptable	Increase roll damping slightly
Slight	No	Cancel inputs	Acceptable	Yes	Yes	Acceptable, unsatisfactory	Increase damping
No	No	Anticipate roll	Acceptable	------	Yes	Marginal	Increase roll damping
No	No	Anticipate roll	Response rate varies	No	Yes	Marginal	Increase roll damping, decrease roll sensitivity
No	No	Anticipate roll	Acceptable	------	Yes	Acceptable, unsatisfactory	Increase damping
Slight	Slight	Provide damping	Too sensitive	Force light	Yes	Acceptable, unsatisfactory	Increase damping and force
Slight	No	Care on inputs	Acceptable	Yes	Yes	Acceptable	Increase roll damping
Slight	No	Provide damping	Acceptable	Yes	Yes	Marginal	Increase roll damping
No	Yes	Anticipate lag	Good small deflection	Response too high	Yes	Not acceptable	Increase roll damping, decrease lag
No	Slight	Anticipate roll	Acceptable	No	Yes	Not acceptable	Increase roll damping
No	No	Care, sensitive	Good	No	Yes	Not acceptable	Increase damping
Yes	No	Anticipate roll	Acceptable	Yes	Yes	Marginal	Increase damping, decrease rate
Yes	Yes	Anticipate roll	Acceptable	Yes	Yes	Marginal	Cut sensitivity, decrease rate buildup
No	No	Large inputs	High force deflection	No	No	Marginal	Increase roll rate, decrease wheel force, deflection
No	No	No	Forces too high	Yes	No	Not acceptable	Increase roll rate, decrease forces
No	No	No	Spongy feeling	Force high	No	Not acceptable	Increase roll rate
No	Slight	No	Yes acceptable	Low sensitivity	Maybe	Fair, low response	Increase response slightly
No	No	No	Marginally acceptable	No, force high	Yes	Marginally acceptable	Increase roll rate
No	No	No	Force little high	Yes	Yes	Acceptable	Decrease force slightly
No	No	No	Acceptable	Yes	Yes	Acceptable	----------------
No	No	No	Very good	Yes	Yes	Acceptable, good	----------------
Slight	No	No	Very good	Yes	Yes	Acceptable	Increase damping slightly
---	------	------	----------------	------	------	Acceptable	----------------

TABLE 3. – SUMMARY OF PILOT

Test condition	$L_{\delta_a}\delta_{a_{max}}$, rad/sec^2	τ_R, sec	$(p_{ss})_{max}$, deg/sec	Pilot	Pilot rating	Question A	B	C	D	E	F
85	1.0	1.0	60	B	3	Good	Fair	Good	Acceptable, high	Yes	Low
86	1.0	1.0	60	B	3	----------	Acceptable	Good	Acceptable	Yes	Little weak
87	1.0	1.0	60	C	2.5	OK	OK	OK	Acceptable	Yes	Acceptable, low
88	1.0	1.0	60	C	3.5	----------	----------	------------	Acceptable	-----	Acceptable, slightly low
89	1.0	1.0	60	E	4	Acceptable	Fair	Good	Acceptable	No	Low
90	1.0	3.0	180	A	4	Satisfactory	Slow, average	Average	Acceptable, high	No	Low
91	1.0	3.0	180	B	5.5	Acceptable	Poor	Poor	Acceptable	Yes	Not acceptable, low
92	1.0	3.0	180	B	5.5	Acceptable	Good, slow	Acceptable	Too much	No	Very low
93	1.0	3.0	180	B	7	Acceptable	Fair	Fair	Too high	No	Not acceptable, low
94	1.0	3.0	180	C	4.5	Fairly good	Fair	Fair	Little high	No	Poor
95	1.0	3.0	180	D	5	Fair	Poor	Good	Acceptable	No	Low
96	1.0	10	600	A	6	Poor	----------	------------	Too high	No	Poor very low
97	1.0	10	600	B	5.5	Good	Good, slow	Acceptable	Rate too high	No	Very low, poor
98	2.0	.1	12	A	5	Fair	Fair	Poor	Too low	Yes	Good
99	2.0	.1	12	B	4	Good	Good	Good	Acceptable, but low	Yes	Excellent
100	2.0	.35	42	A	2	Good	Good	Good	Acceptable	Yes	Acceptable
101	2.0	.35	42	B	2.5	Good	Excellent	Good	Acceptable	Yes	Good
102	2.0	.35	42	B	3	Good	Good	Good	Acceptable, little low	Yes	Good
103	2.0	.35	42	C	1.5	Real good	Real good	Real good	Acceptable, little high	Yes	Nice
104	2.0	.35	42	E	2	Acceptable	Good	Good	Acceptable	No	Good
105	2.0	1.0	120	A	2	----------	----------	Good	Response high	No	Nice, good
106	2.0	1.0	120	A	4	Good	Very good	Good	Acceptable, too much	No	Acceptable
107	2.0	1.0	120	A	4.5	----------	Good	------------	Extremely high	No	Good
108	2.0	1.0	120	A	3	----------	----------	------------	Acceptable, high		Acceptable, slightly low
109	2.0	1.0	120	B	3.5	Good	Fair	Acceptable	Too high	No	Marginal
110	2.0	1.0	120	C	4	Fairly good	Fair	Fair	Can't use all rate	Yes	Not bad
111	2.0	1.0	120	C	4	Acceptable	Acceptable	Acceptable	Too high	No	Acceptable, marginal
112	2.0	1.0	120	C	4.5				Acceptable, too high		Acceptable, low
113	2.0	1.0	120	D	4	Poor	Fair	Good	High	No	Low
114	2.0	3.0	360	A	5	Good	Good	Good	Acceptable, high	Sensitive no	Low
115	2.0	3.0	360	B	5	Acceptable	Fair	Fair	Not acceptable, too high	No	Not acceptable, too low
116	2.0	3.0	360	C	6	Fair	Poor	Not bad	Too high	No	Too low
117	2.0	3.0	360	E	5	Fair	Fair	Fair	Not acceptable, high	No	Very poor
118	2.0	10	1200	A	7.5	Difficult	Fair	------------	Too high	No	Very little
119	2.0	10	1200	A	7	Poor	Difficult	Poor	Too high	No	Very poor
120	2.0	10	1200	A	7	Poor	Poor	Good	Acceptable, high	No	Not acceptable, very low
121	2.0	10	1200	B	8	Acceptable	Poor	Marginal	Too high	No	Not acceptable, low
122	2.0	10	1200	C	8	Poor	Poor	Poor	Not acceptable, high	No	Not acceptable, low
123	3.5	.1	21	A	3	Very good	Good	Good	Acceptable	Yes	High
124	3.5	.1	21	B	3	Excellent	Excellent	Excellent	Acceptable	Yes	Very good
125	3.5	.1	21	C	2.5	Good	Good	Good	Good	Yes	Very acceptable
126	3.5	.35	73	A	4.5	Good	Good	Good	Acceptable, little high	Could	Good

COMMENT DATA - Continued

(table 1)

G	H	I	J	K	L	M	N
No	No	No	Fairly good, acceptable	Yes	Yes	Acceptable	Increase roll damping
No	No	Anticipate roll out	Acceptable	Yes	Yes	Acceptable	Increase roll damping
Slight	No	Lead roll out	Good	Yes	Yes	Acceptable	Slightly decrease rate and increase damping
---	------	------	----------------	------	------	Acceptable	----------------
Slight	No	No	Acceptable	Yes	Yes	Not bad	Increase damping
Slight	No	Provide damping	Acceptable	Barely	Yes	Acceptable unsatisfactory	Improve damping
No	Slight	Provide damping	Acceptable	Marginal	Yes	Marginal	Increase damping
Slight	------	Anticipate roll	Light forces	Response high	Yes	Not acceptable	Increase damping
No	No	Anticipate roll	Too responsive, low force	Yes	Yes	Not acceptable	Increase roll damping, decrease roll rate
Slight	No	Lead roll out	OK	Barely	------	Acceptable, unsatisfactory	Increase damping, decrease response
Slight	No	Anticipate roll	Acceptable, light forces	Yes	Yes	Marginal	Cut rate, increase damping
Yes	No	Use small inputs	Extremely sensitive	No	No	Barely acceptable	Cut sensitivity, increase damping
No	No	Anticipate roll	Acceptable	High rates, no	Yes	Not acceptable	Increase roll damping, cut roll power
No	No	No	Fairly acceptable, force high	Yes	No	Acceptable, unsatisfactory	Increase roll rate
No	No	No	Acceptable, forces high	Wheel forces high	Yes	Acceptable	Increase roll rate, decrease forces
No	No	No	Acceptable	Yes	Yes	Acceptable	Increase sensitivity slightly
No	No	No	Acceptable	Yes	Yes	Acceptable	Decrease force, increase roll rate
No	No	No	Acceptable high force	No	Yes	Acceptable	Decrease wheel force deflection slightly
No	No	No	Yes, acceptable	Yes	OK	Overall great	Improve wheel centering
No	No	No	Acceptable	Yes	Yes	Acceptable	None
No	No	No	----------------	------	------	Acceptable	
Slight	No	No	Too sensitive	No	Yes	Acceptable, unsatisfactory	Cut roll sensitivity
No	No	Careful inputs	Too sensitive	No	Marginal	Acceptable, unsatisfactory	Decrease roll response
						Acceptable	
No	No	No	Acceptable, responsive	Yes	Yes	Barely acceptable	Increase damping, decrease roll rate
Slight	No	No	OK	Yes	Yes	Acceptable, unsatisfactory	Increase roll damping
No	No	No	Forces light	------	Yes	Acceptable	Increase damping
						Acceptable, unsatisfactory	
Slight	No	Anticipate roll	OK	Yes	Yes	Marginal	Decrease roll rate, increase damping
Slight	No	Careful on inputs	Acceptable but light	No	Too sensitive	Marginal	Decrease roll rate, increase damping
No	No	Anticipate roll	Acceptable, force light	No	Yes	Not acceptable	Increase damping, decrease roll rate
No	------	No	Force-deflection low	No	Yes	Not acceptable	Decrease response, increase damping
Slight	No	Careful inputs	High sensitivity	High response	Yes	Not acceptable	Cut sensitivity
Yes	No	Careful inputs	Very sensitive	No	No	Not acceptable	Increase damping
Slight	No	Careful of inputs	Forces light	No	No	Not acceptable	Increase damping
Yes	No	Provide damping	Acceptable	Barely	No	Not acceptable	Increase damping, decrease sensitivity
Slight	No	Careful of inputs	Forces too light	No	Yes	Not acceptable	Decrease rate, increase damping
No	No	Watch, sensitive	Forces too low	No	Yes	Not acceptable	Increase damping, decrease response, sensitivity
No	Slight	No	Acceptable	Yes	Yes	Acceptable	Increase control sensitivity or decrease damping slightly
No	No	No	Force-deflection little high	Yes	Yes	Acceptable	Slightly increase roll rate, decrease forces
No	No	No	Acceptable	------	Yes	Acceptable	Increase roll rate slightly
Slight	No	Easy on inputs	Acceptable, low forces	Sensitive, no	Yes	Marginal	Decrease roll rate, increase forces

TABLE 3. – SUMMARY OF PILOT

Test condition	$L_{\delta_a}\delta_{a_{max}}$, rad/sec^2	τ_R, sec	$(p_{ss})_{max}$, deg/sec	Pilot	Pilot rating	Question A	B	C	D	E	F
127	3.5	.35	73	A	2.5	Good	Good	Good	Acceptable	No	Acceptable
128	3.5	.35	73	B	2.5	Very good	Good	Good	Acceptable, high	Yes	Very good
129	3.5	.35	73	C	2	Very good	Very good	------------	Little high	Yes	Good
130	3.5	.35	73	D	3	Good	Good	Good	Acceptable, high	Yes	Good
131	3.5	.35	73	E	3	Fair	Good	Good	Acceptable, high	No	Good
132	3.5	1.0	210	A	5	Good	Fair	Good	Acceptable, high	Sensitive, no	Acceptable
133	3.5	1.0	210	B	7	Good	Fair	Acceptable	Much too high	No	Acceptable, low
134	3.5	1.0	210	B	7	Acceptable	Fair	Fair	Not acceptable, high	No	Marginally acceptable
135	3.5	1.0	210	C	4	Good	Fair	Fair	Rate too high	No	Fair
136	3.5	3.0	630	A	7	Poor	Poor	Poor	Not acceptable, high	No	Low
137	3.5	3.0	630	B	7	Acceptable	Fair	Fair	Not acceptable, too high	No	Not acceptable, low
138	3.5	3.0	630	C	6	Poor	Fair	------------	Not acceptable, high	No	Not acceptable, low
139	3.5	3.0	630	D	7	Poor	Poor	Fair	High	No	Not acceptable, low
140	3.5	10	2100	A	7	Difficult	Difficult	Difficult	Not acceptable, too high	No 1/3	Not acceptable, very low
141	3.5	10	2100	B	6.5	Fair	Fair	Poor	Not acceptable, too much	No	Poor, very low
142	3.5	10	2100	C	6.5	Fair	Fair	Fair	Not acceptable, too high	No	Not acceptable, too low
											Selecting optimum
143	3.5	.23	48	B	2.5	Good	Good	Good	Acceptable, high	Yes	Acceptable
144	2.0	.31	37	B	3	Very good	Good	Good	Acceptable	Yes	Acceptable
145	1.0	.48	29	B	5	Good	Fair	Acceptable	Acceptable, low	Yes	Acceptable
146	1.0	.50	30	B	4	Good	Fair	Good	Acceptable	Yes	Acceptable
147	3.5	.26	55	B	3	Good	Good	Good	Acceptable, little high	No	Acceptable
148	2.0	.35	42	A	2	Good	Good	Good	Acceptable	Yes	Good
149	1.0	.54	32	A	3	Good	Fair	Good	Acceptable	Yes	Slightly low
150	3.5	.20	42	A	1.5	Good	Good	Good	Acceptable	Could	Acceptable
151	1.0	.50	30	A	3	Good	Fair	Good	Acceptable, low	Yes	Little low
152	1.0	.61	36	A	3	Good	Fair	------------	Acceptable, low	-----	Low

COMMENT DATA - Concluded

(table 1)

G	H	I	J	K	L	M	N
No	No	No	Acceptable	Yes	Yes	Acceptable satisfactory	----------------
No	No	No	Acceptable	Yes	Yes	Acceptable	Decrease roll rate slightly
No	No	No	Acceptable	Yes	Yes	Acceptable	Decrease wheel forces
No	No	No	Acceptable, light forces	Yes	Yes	Acceptable	Cut sensitivity
Slight	No	No	Light forces	Yes	Yes	Acceptable	Increase forces, cut sensitivity
Slight	No	Careful on inputs	Light forces	No	Yes	Responses high marginal	Decrease roll rate
Slight	No	Careful inputs	Too sensitive	No	Yes	Not acceptable	Decrease roll rate
Slight	No	Small deflection only	Not acceptable, forces light	No	Not safely	Not acceptable	Decrease roll rate, increase damping slightly
No	No	No, forces low	Deflection small	No	Yes	Acceptable, unsatisfactory	Lower roll rate
Slight	No	Careful on inputs	Too sensitivie	No	No	Not acceptable	Decrease response
Slight	No	Anticipate roll	Force-deflection low	No	Yes, safely?	Not acceptable	Decrease roll rate, increase damping
No	No	No	Forces light	------	Yes	Acceptable, unsatisfactory	Increase damping, decrease response
Yes	No	Careful inputs	Forces light	Yes	Yes	Not acceptable	Cut roll rate, increase damping
Yes	No	Care on inputs	Force light, sensitive	No	No	Not acceptable	Increase damping, decrease response
Yes	No	Small inputs	Forces too low	No	Yes, care	Not acceptable	Cut roll response, increase wheel force
Slight	No	Provide damping	Light forces, care	No	Yes	Not acceptable	Increase damping
damping and response							
No	No	No	Force little high	------	Yes	Acceptable	Slightly decrease wheel force
No	No	No	Force little high	Yes	Yes	Acceptable	Decrease wheel force, increase roll rate slightly
No	No	Large inputs	Force little high	------	Yes	Acceptable, unsatisfactory	Decrease wheel force, increase roll rate slightly
No	No	No	Acceptable	------	Yes	Acceptable	Decrease wheel force, increase roll rate slightly
No	No	No	Acceptable	Yes	Yes	Acceptable	Decrease roll rate slightly
No	No	No	Acceptable	Yes	Yes	Acceptable	----------------
No	No	No	Acceptable	Yes	Yes	Acceptable	Increase rate damping slightly
No	No	No	Acceptable	Yes	Yes	Acceptable	Nice feel
No	Slight	No	Good	Yes	Force high	Acceptable	Decrease force slightly
No	No	No	Good	Yes	Yes	Acceptable	Increase roll rate slightly and damping

TABLE 4. – COMPARISON OF GROUND AND FLIGHT PILOT RATINGS

$L_{\delta_a}\delta_{a_{max}}$, rad/sec^2	τ_R, sec	Ground: Average pilot rating	Ground: Number of ratings	Flight: Average pilot rating	Flight: Number of ratings
0.05	0.35	10.0	2	9.0	1
.05	10.0	6.0	1	7.3	3
.1	.35	7.7	2	8.1	3
.1	1.0	8.0	1	7.2	4
.1	3.0	4.0	1	6.5	3
.1	5.0	7.5	1	6.0	3
.1	10.0	7.0	1	6.6	4
.2	.1	9.2	1	9.4	2
.2	.35	8.3	3	7.2	4
.2	1.0	7.5	1	5.1	3
.2	3.0	5.0	2	4.5	6
.2	10.0	5.7	1	6.2	3
.5	.35	4.0	1	4.9	5
.5	1.0	3.7	2	2.7	8
.5	10.0	4.0	1	5.3	7
1.0	.1	4.0	1	6.0	3
1.0	.35	3.7	2	3.1	4
1.0	1.0	2.0	1	2.5	8
1.0	3.0	5.7	2	5.3	6
1.0	10.0	6.0	3	6.0	2
2.0	.1	7.0	1	4.5	2
2.0	.35	3.0	5	2.2	5
2.0	1.0	3.7	2	3.7	9
2.0	10.0	5.0	1	5.2	5
3.5	.1	3.0	1	2.9	3
3.5	10.0	7.4	4	6.7	3

TABLE 5. – MEASURED RESPONSE CHARACTERISTICS

	Set values	Experimental measurements: Means: Model	Means: Airplane	Standard deviations: Model	Standard deviations: Airplane
τ_R, sec	10	9.56	9.68	1.13	0.97
	5	4.90	4.84	0.16	.47
	3	3.00	3.03	.24	.31
	1	1.03	1.01	.06	.10
	.35	.36	.44	.03	.07
	.1	.12	.18	.03	.05
$L_{\delta_a}\delta_{a_{max}}$, rad/sec^2	3.5	3.45	2.90	0.69	0.83
	2.0	2.07	1.76	.33	.40
	1.0	.98	.85	.11	.18
	.5	.46	.41	.07	.09
	.2	.20	.17	.02	.04
	.1	.10	.09	.02	.02
	.05	.053	.046	.008	.003

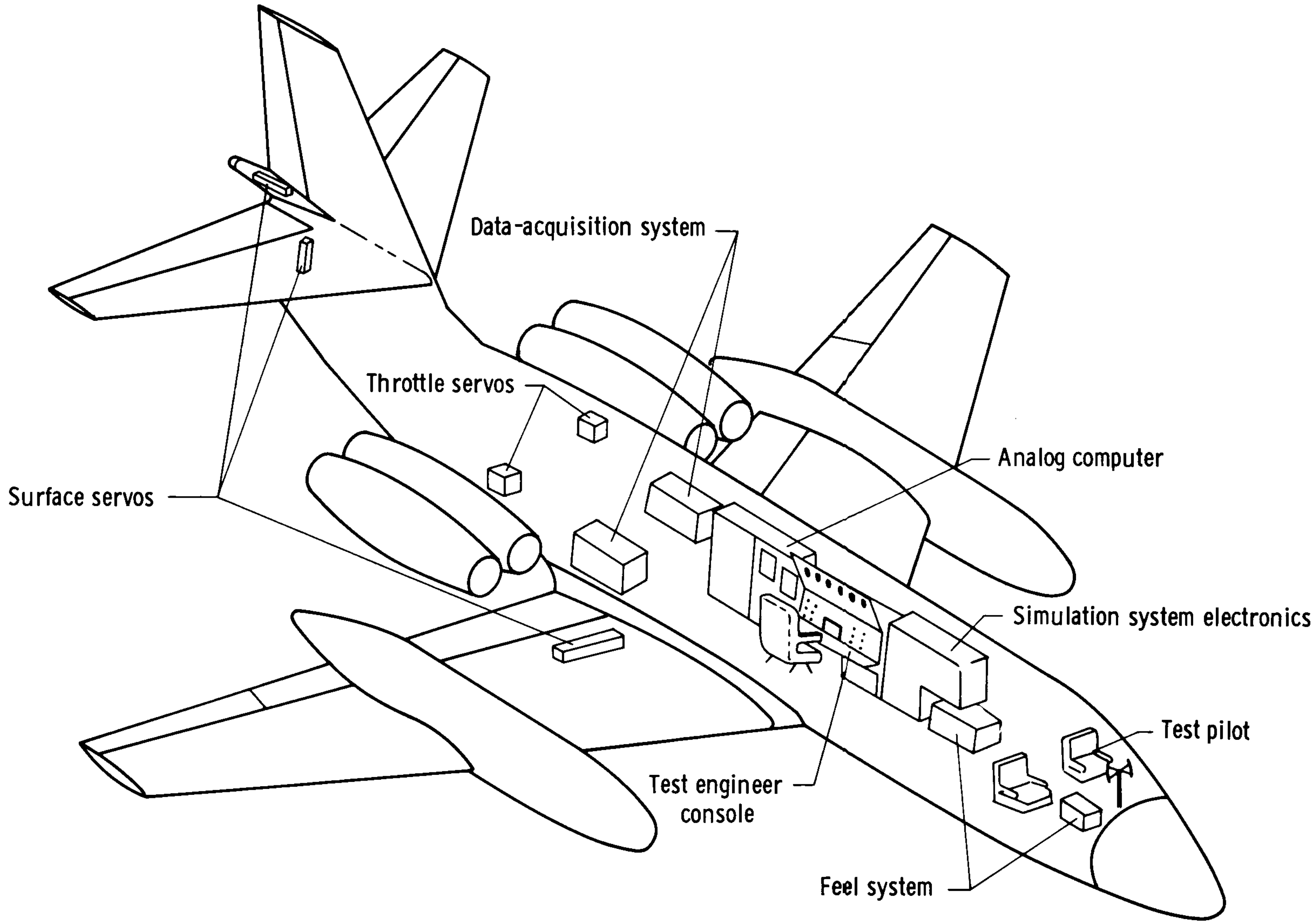


Figure 1. Layout of the JetStar and systems which make up the general purpose airborne simulator.

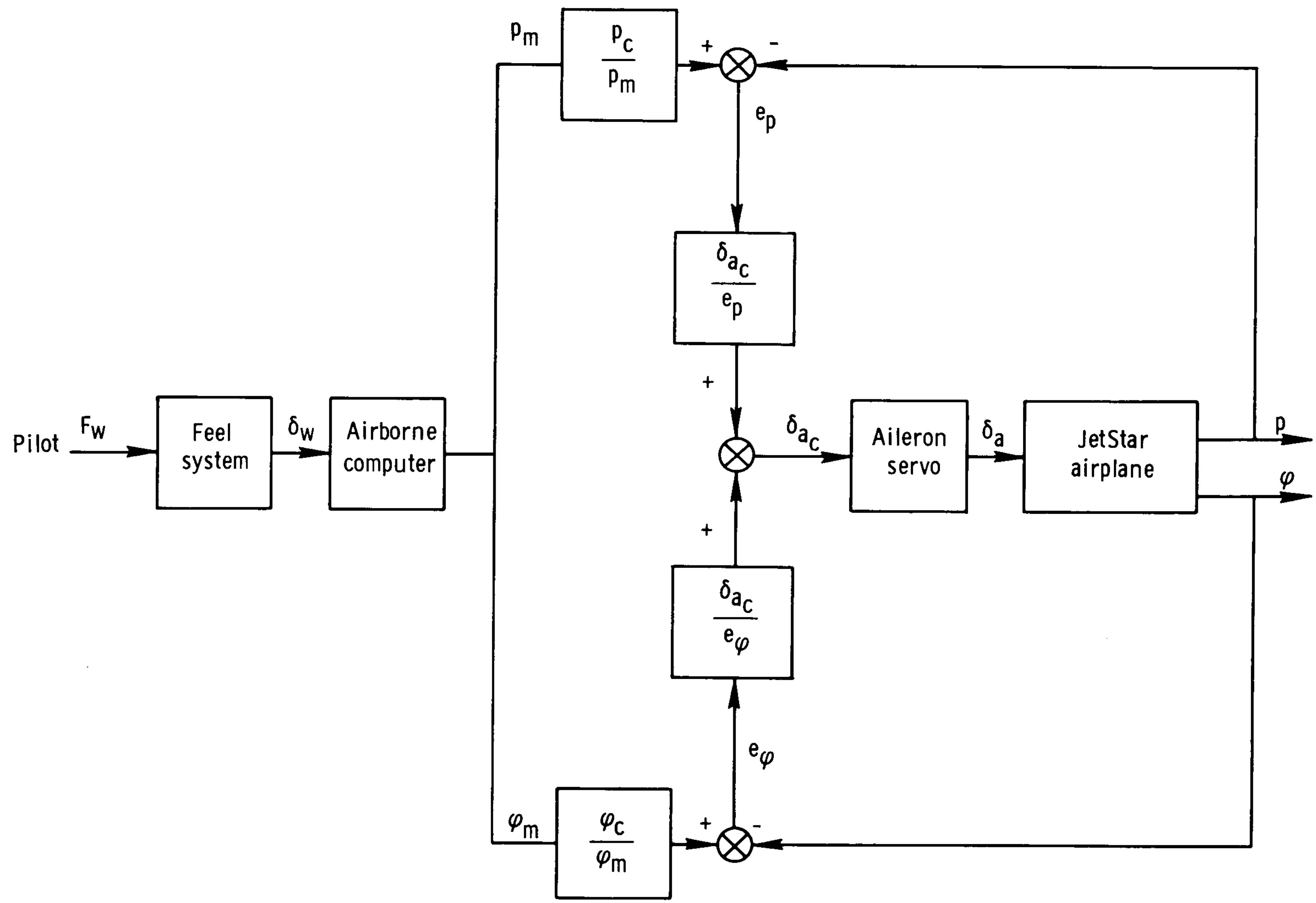


Figure 2. Block diagram of the GPAS model-controlled system. Airborne computer model used $\frac{p}{\delta_a} = \left(\frac{L_{\delta_a}\tau_R}{\tau_R s + 1}\right)$.

Figure 3. Evaluation pilot's station. E-20794

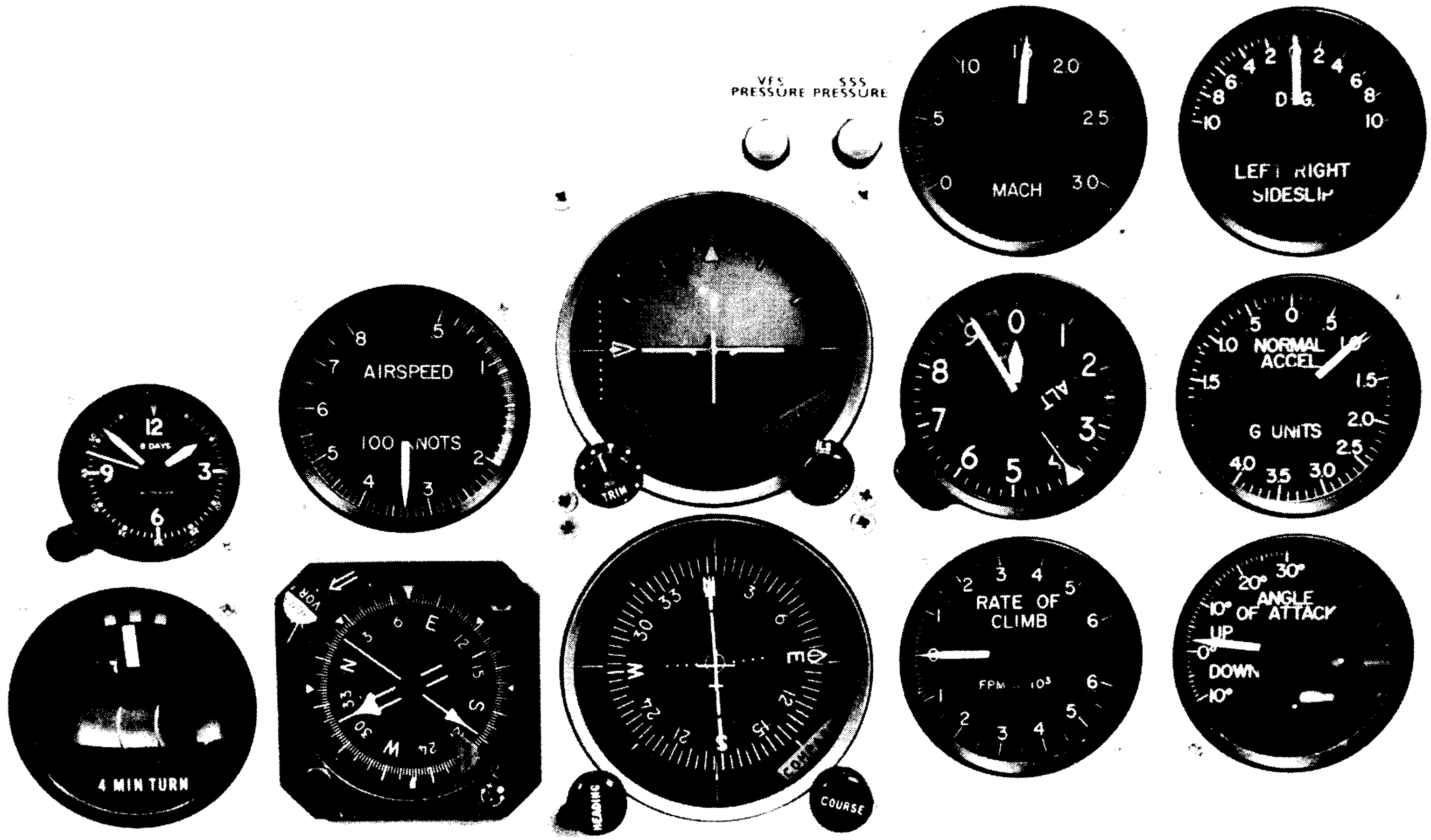
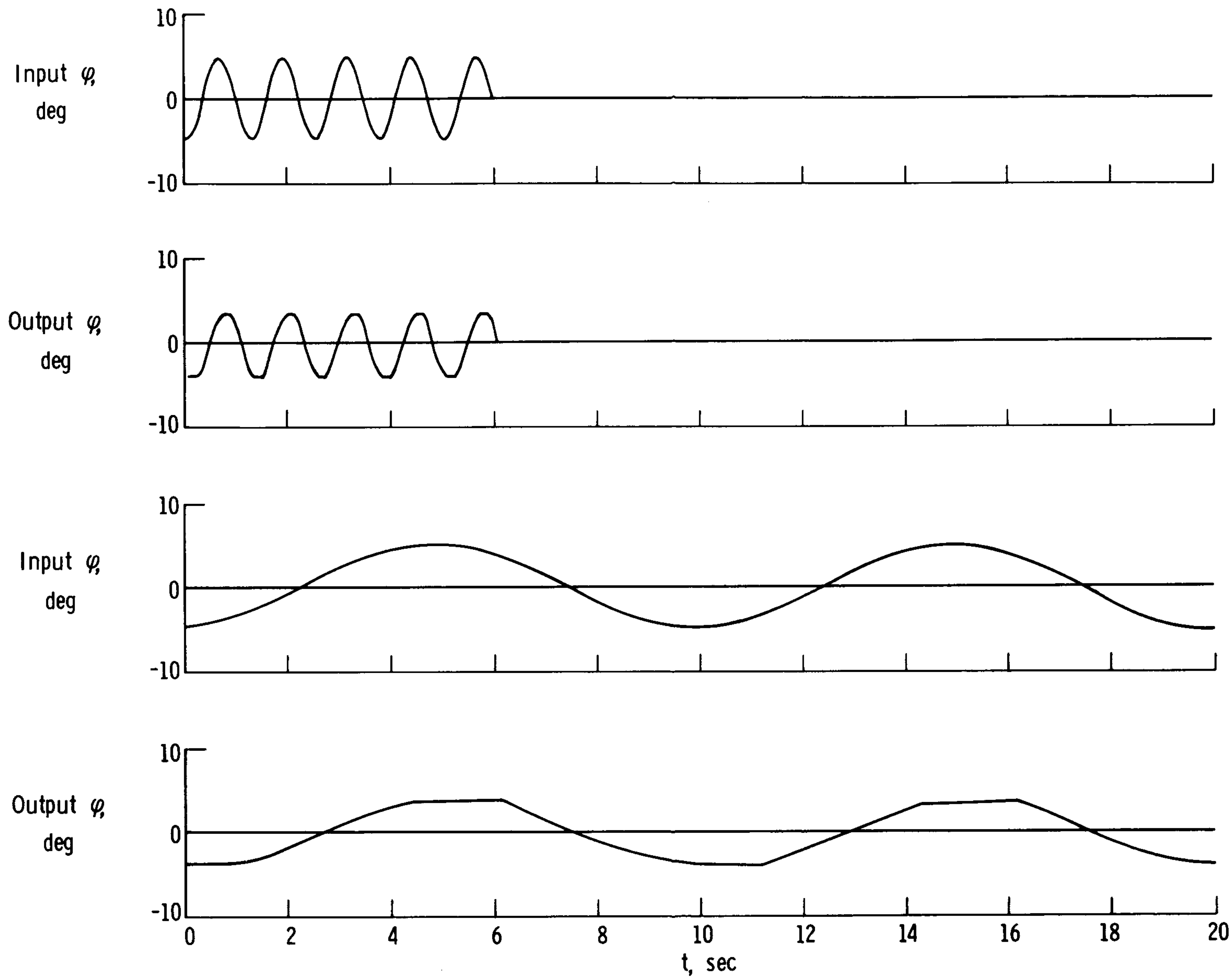
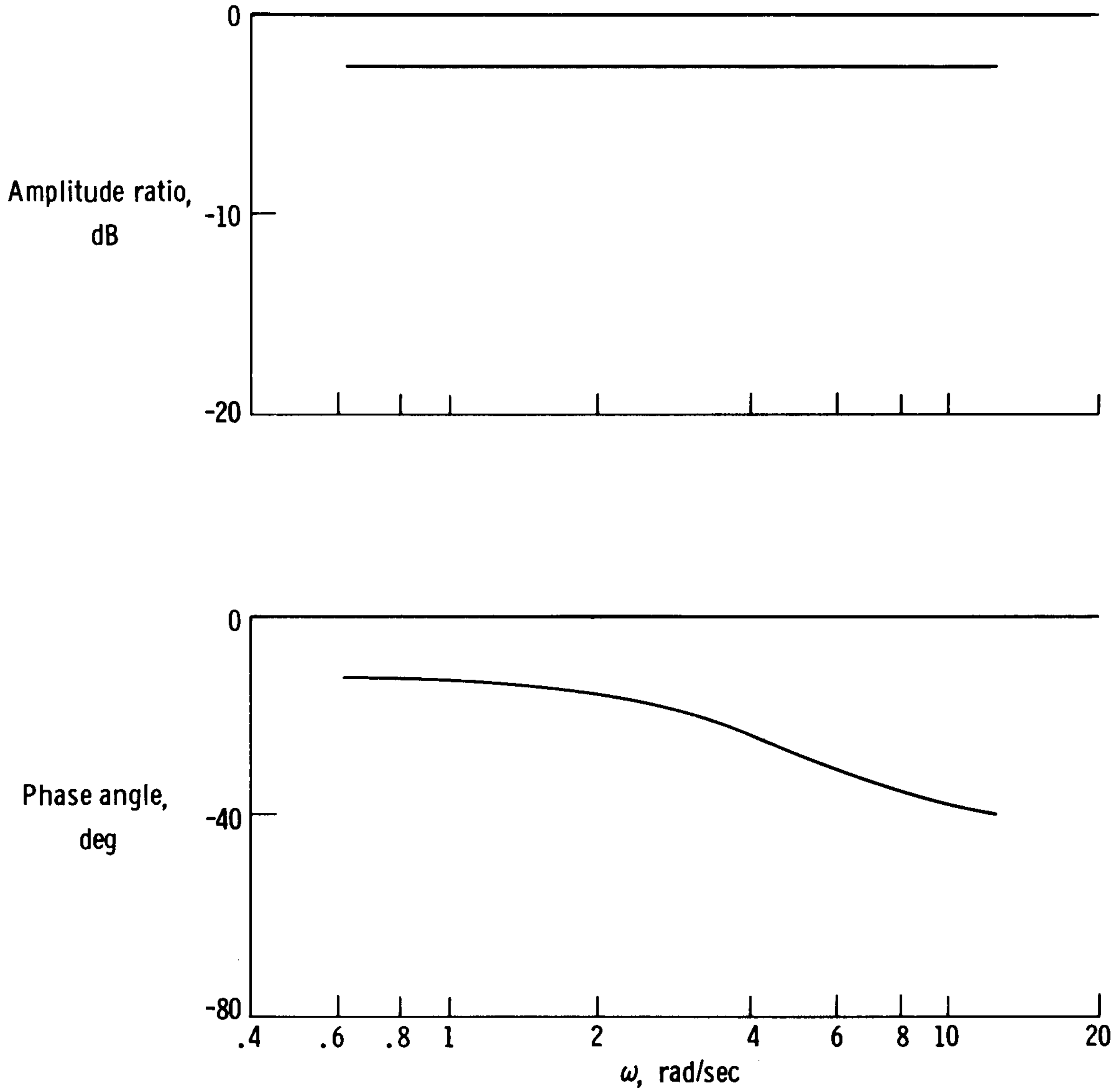


Figure 4. Evaluation pilot's instrument display.



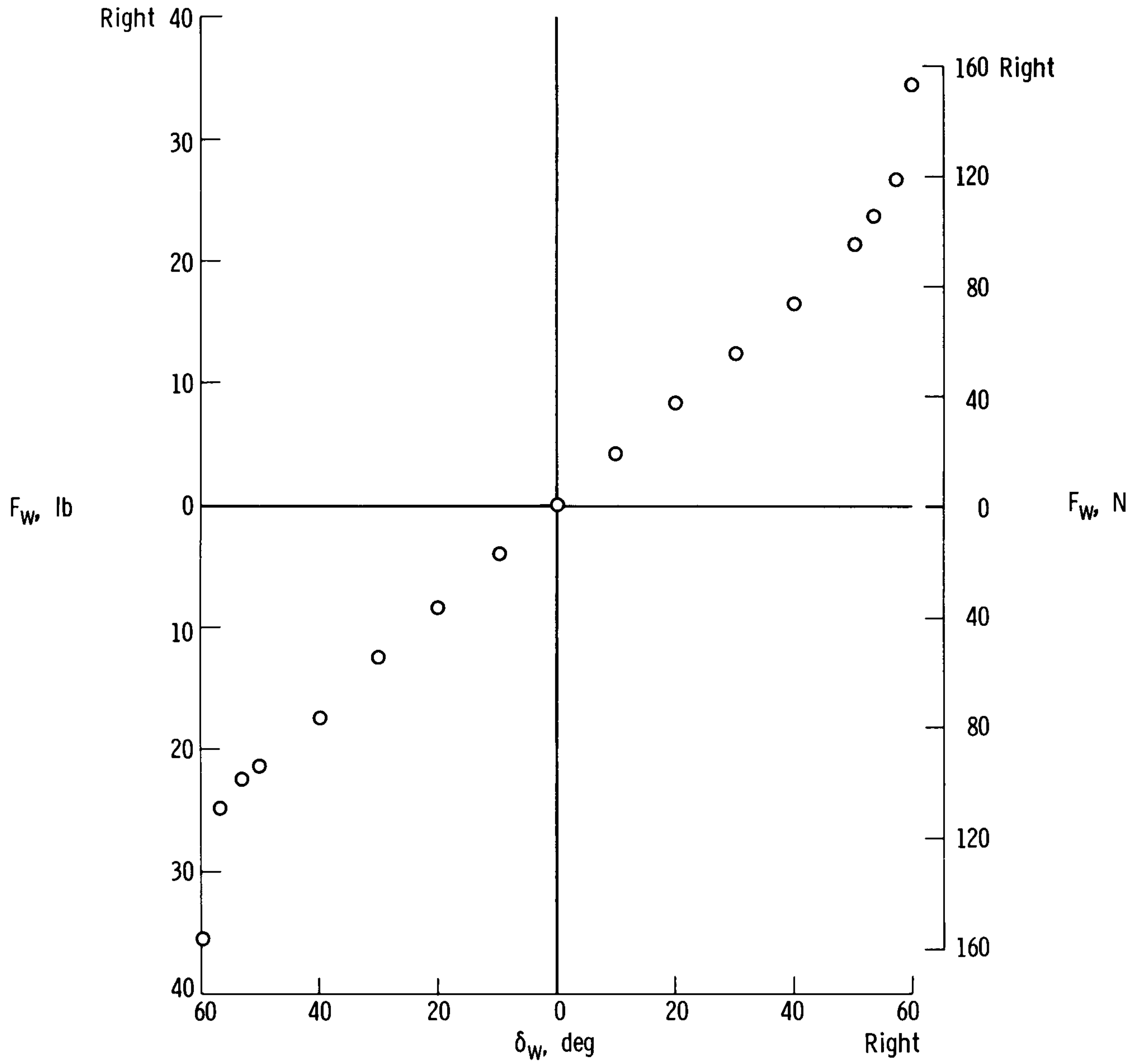
(a) Examples of following at a frequency of 0.8 cps and 0.1 cps.

Figure 5. Frequency-response characteristics of the pilot's roll-attitude instrument.



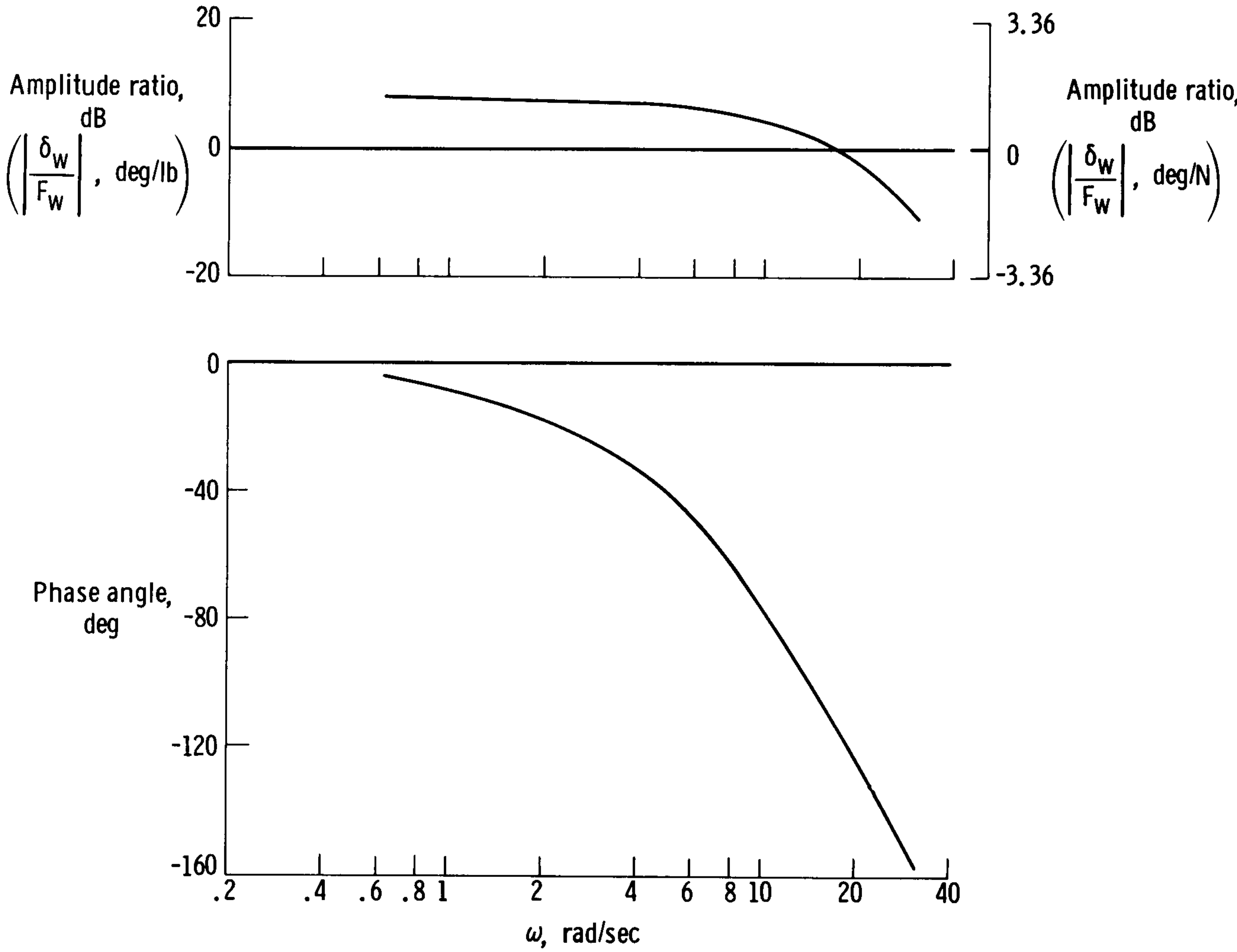
(b) Amplitude and phase of the roll-attitude instrument.

Figure 5. Concluded.



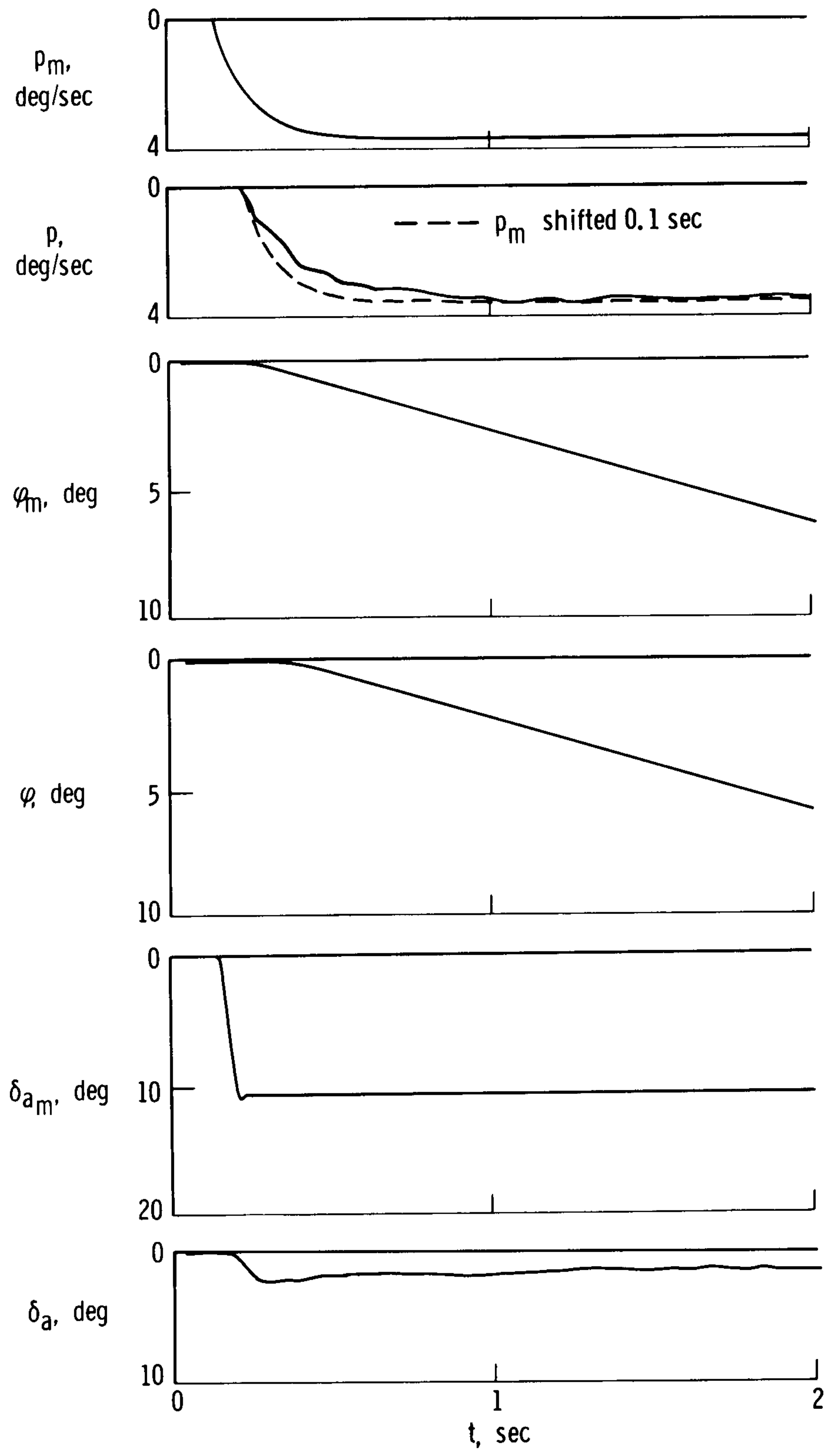
(a) Force gradient used during most of the program.

Figure 6. Control-wheel characteristics.



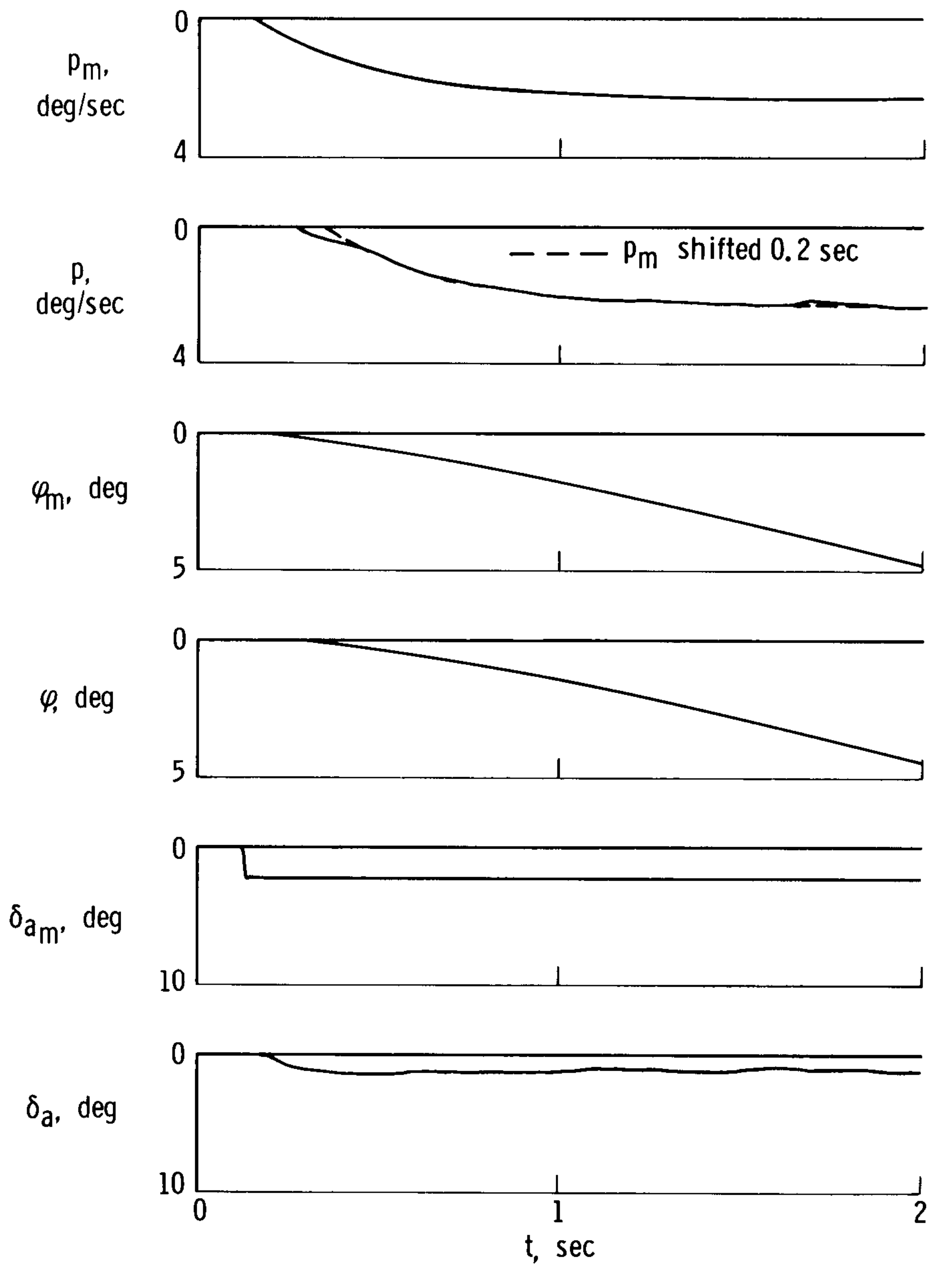
(b) Frequency response of the roll-control feel system.

Figure 6. Concluded.



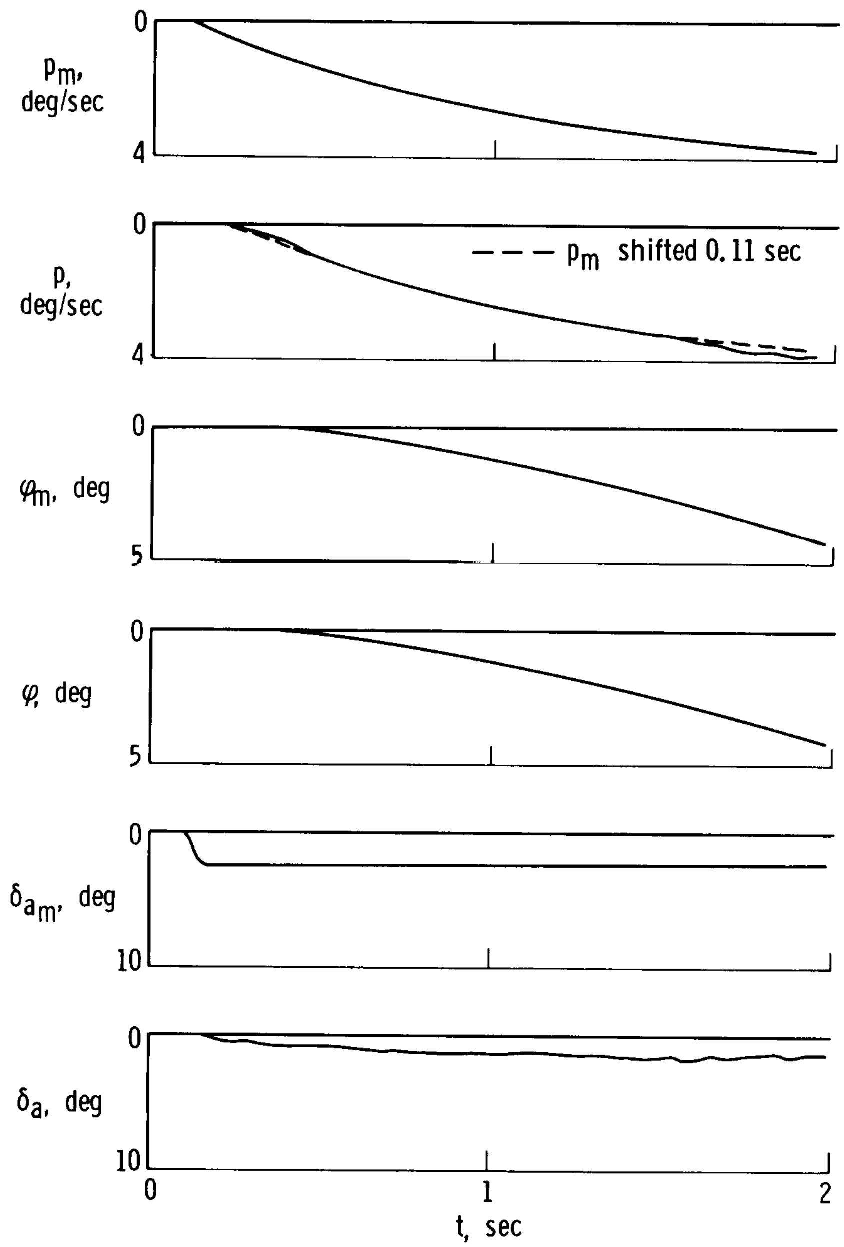
(a) $L_{\delta_a}\delta_{a_{max}} = 3.5$ rad/sec^2; $\tau_R = 0.1$ sec.

Figure 7. Time histories of GPAS following step commands of the aileron model.



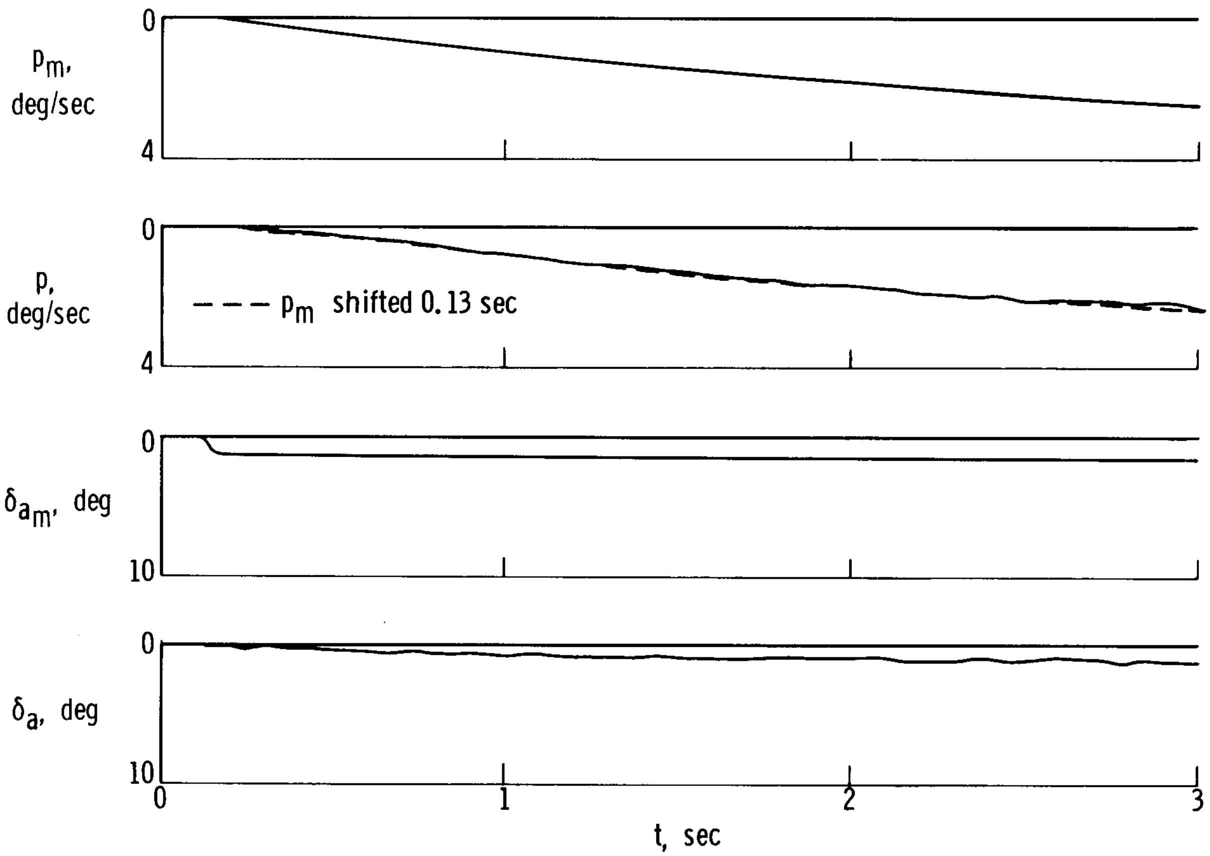
(b) $L_{\delta_a}\delta_{a_{max}} = 3.5$ rad/sec^2; $\tau_R = 0.35$ sec.

Figure 7. Continued.



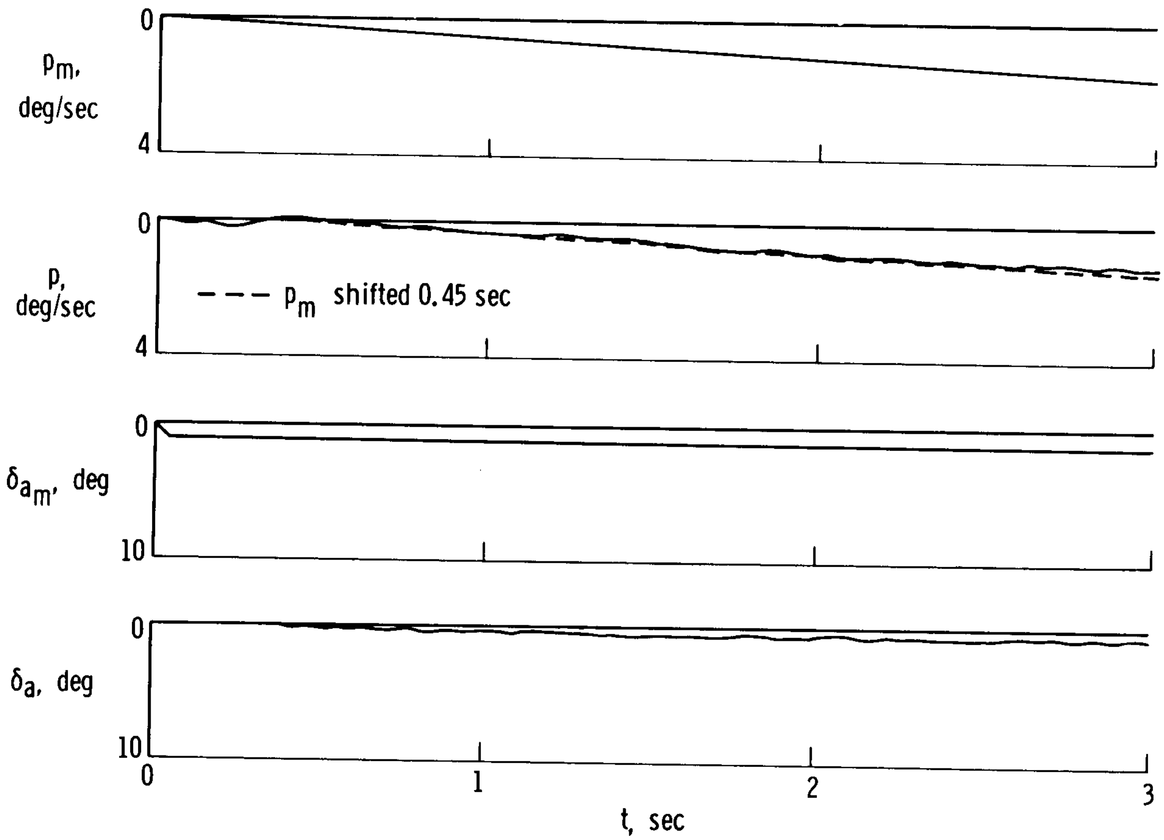
(c) $L_{\delta_a}\delta_{a_{max}} = 2.0$ rad/sec^2; $\tau_R = 1.0$ sec.

Figure 7. Continued.



(d) $L_{\delta_a}\delta_{a_{max}} = 1.0$ rad/sec^2; $\tau_R = 3.0$ sec.

Figure 7. Continued.



(e) $L_{\delta_a}\delta_{a_{max}} = 0.5$ rad/sec^2; $\tau_R = 10.0$ sec.

Figure 7. Concluded.

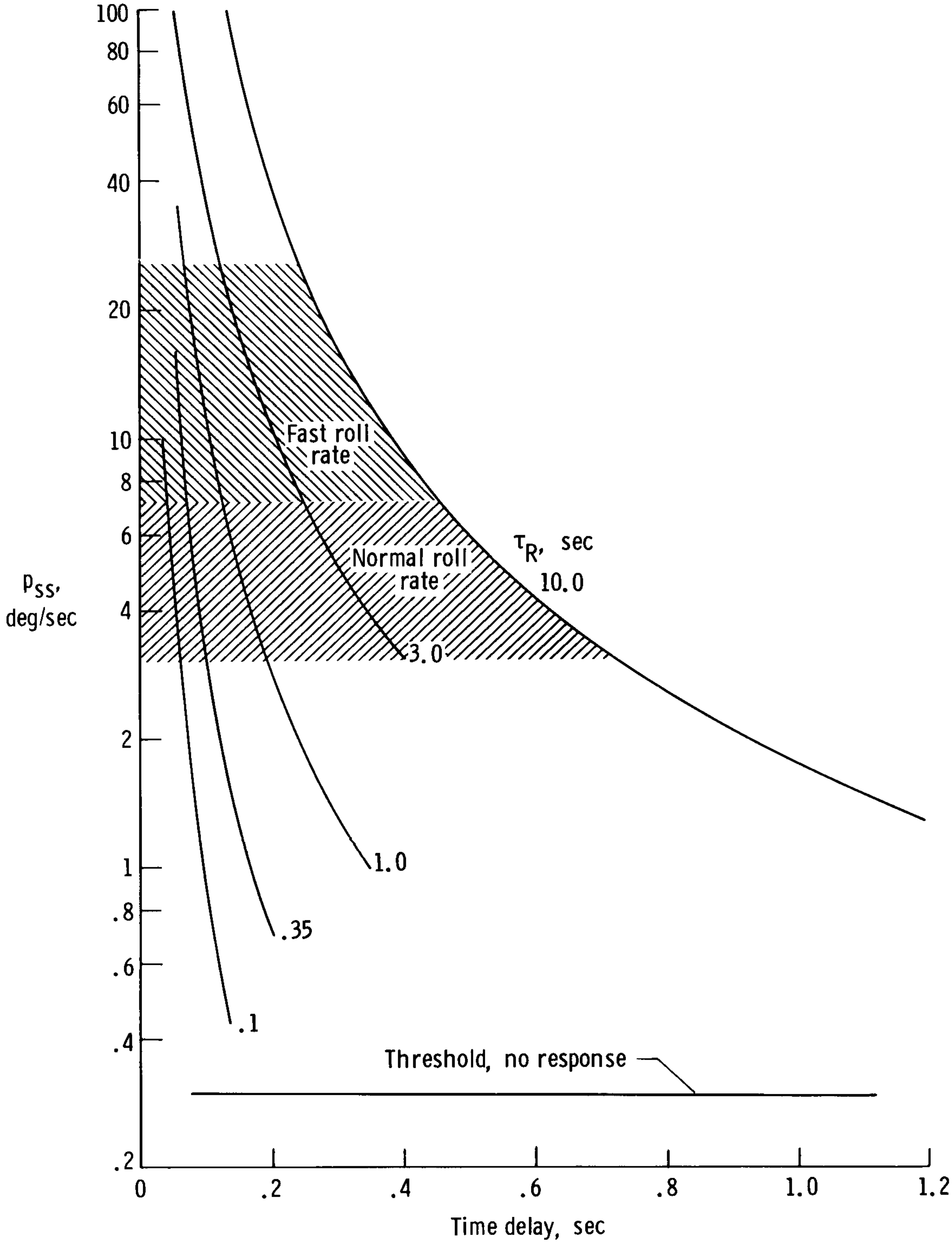


Figure 8. Measured delay time at various levels of roll response and time constants.

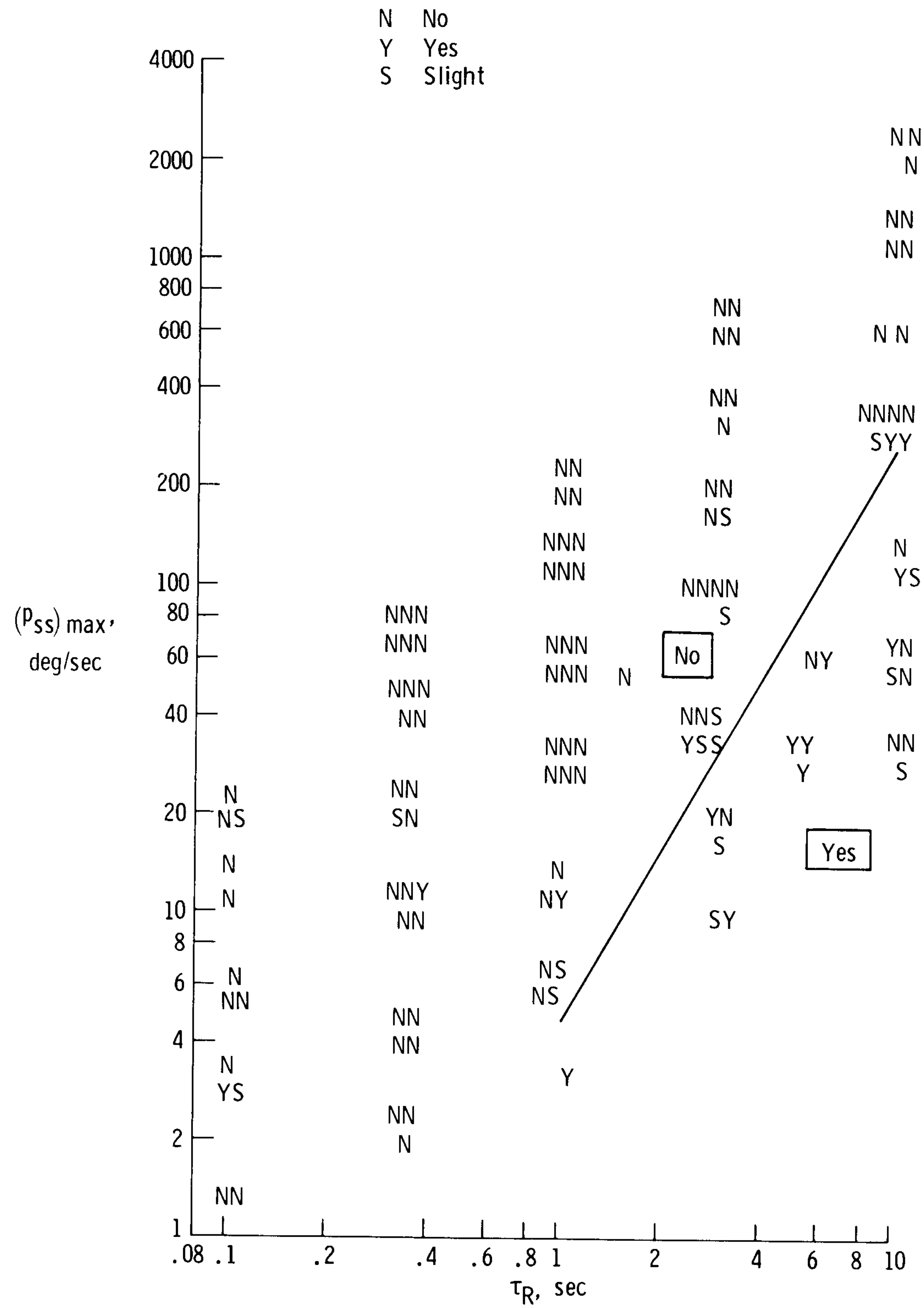


Figure 9. Summary of pilot comments concerning question H (table 1): Was there objectionable lag between wheel and response?

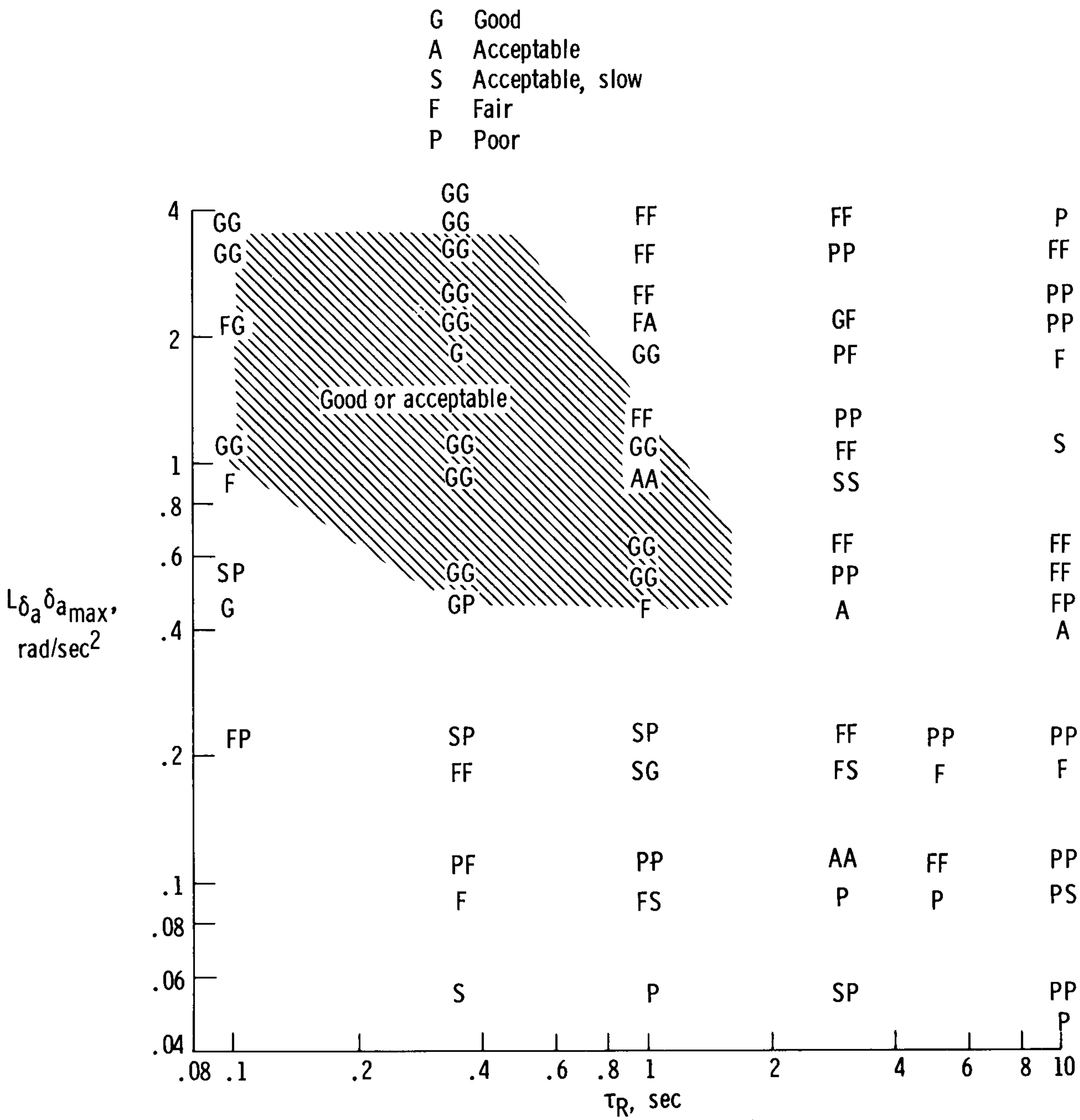


Figure 10. Summary of pilot comments concerning question B (table 1): Ability to roll to and stop at desired bank angle slow, fast.

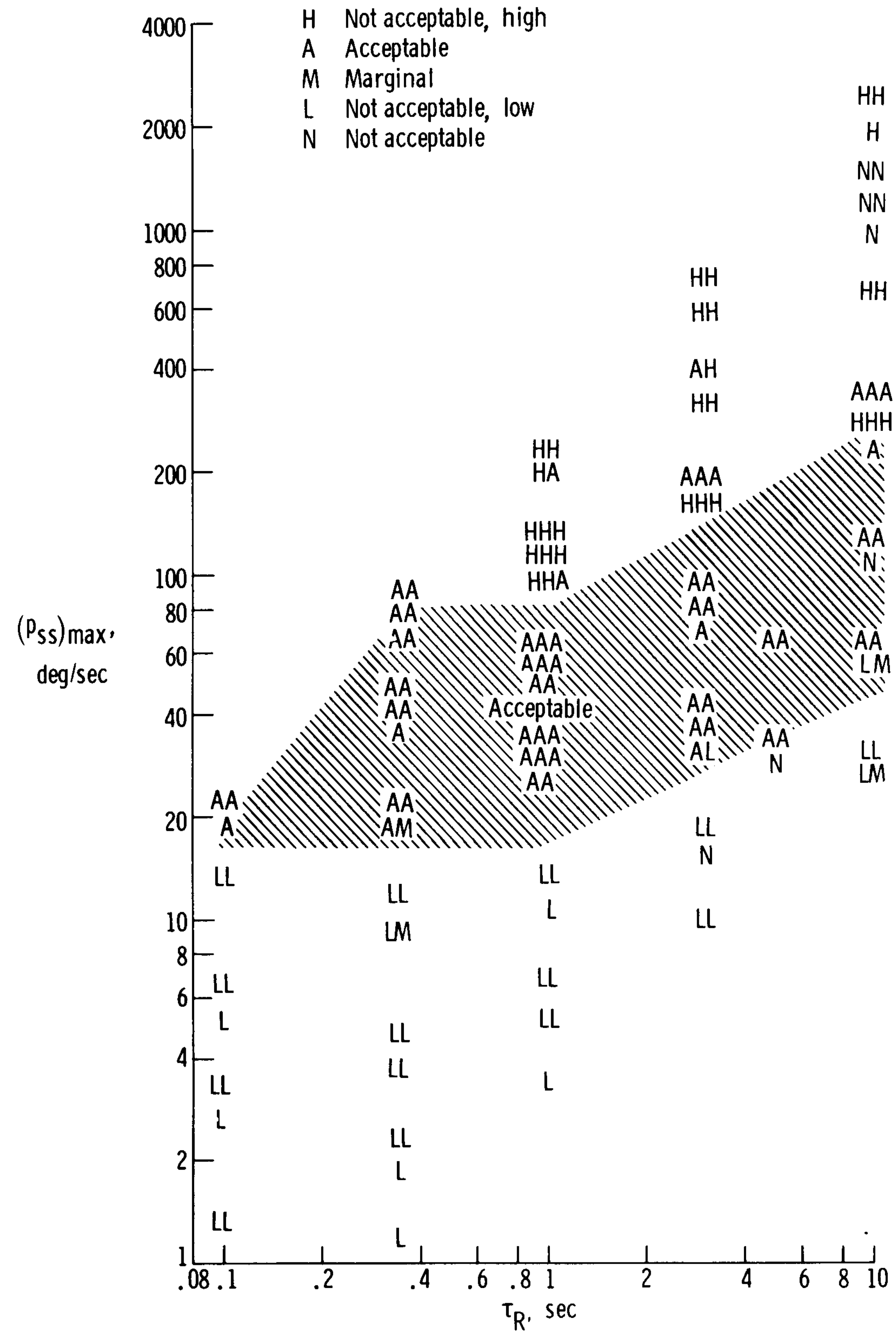


Figure 11. Summary of pilot comments concerning question D (table 1): Is control rate available acceptable for a transport?

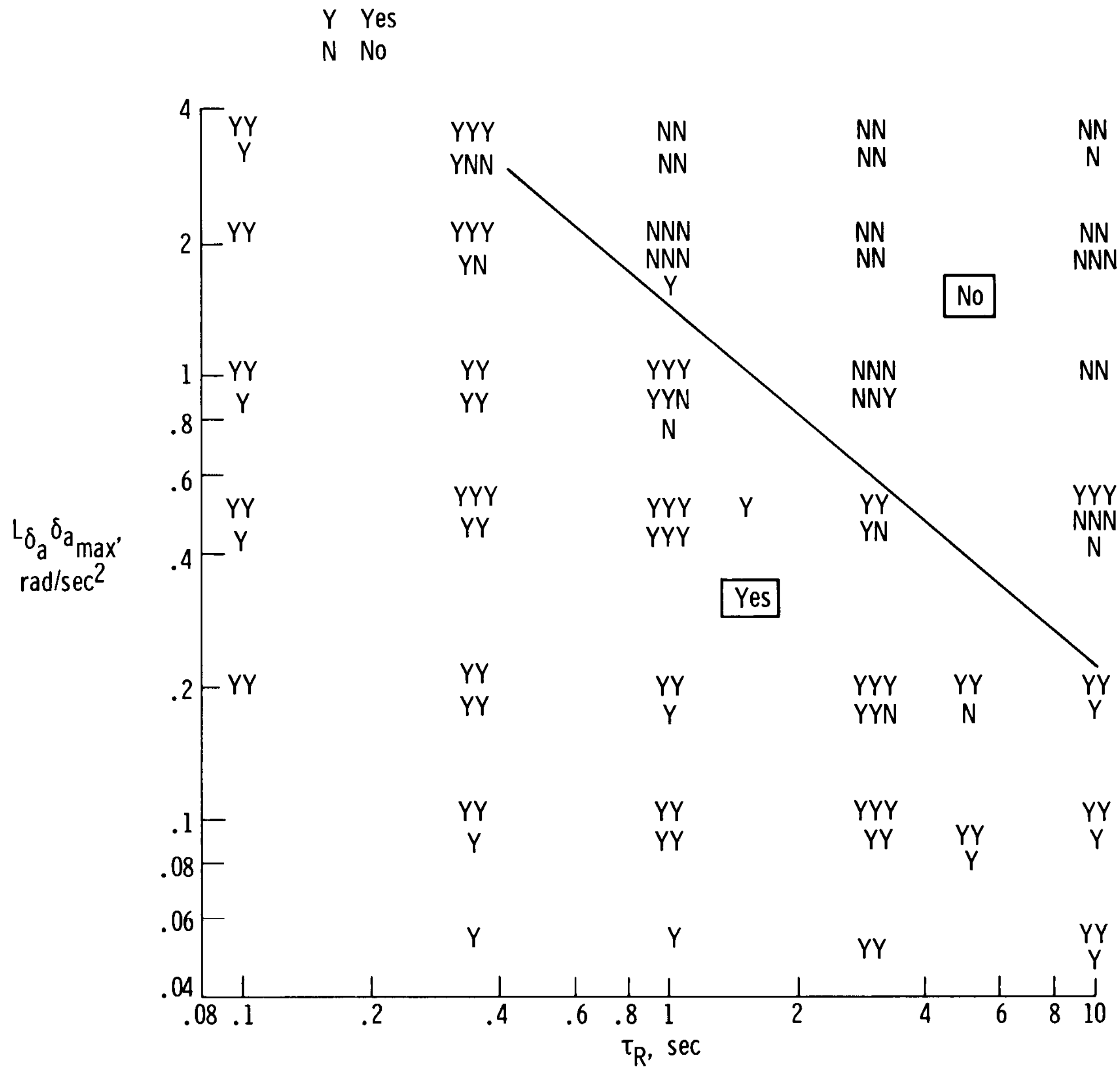


Figure 12. Summary of pilot comments concerning question E (table 1): Could all roll rate (full wheel) be used?

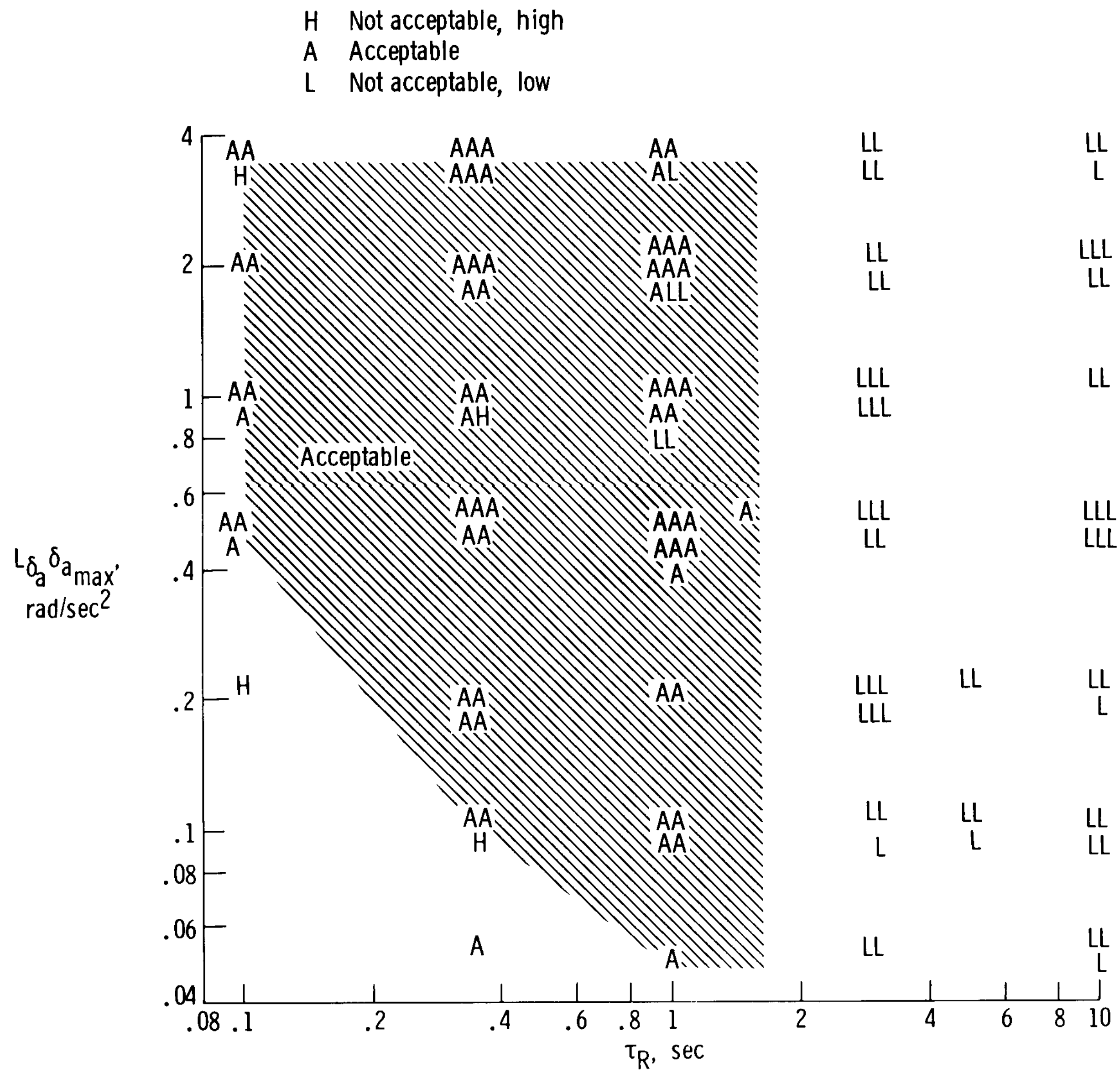


Figure 13. Summary of pilot comments concerning question F (table 1): Was roll damping acceptable?

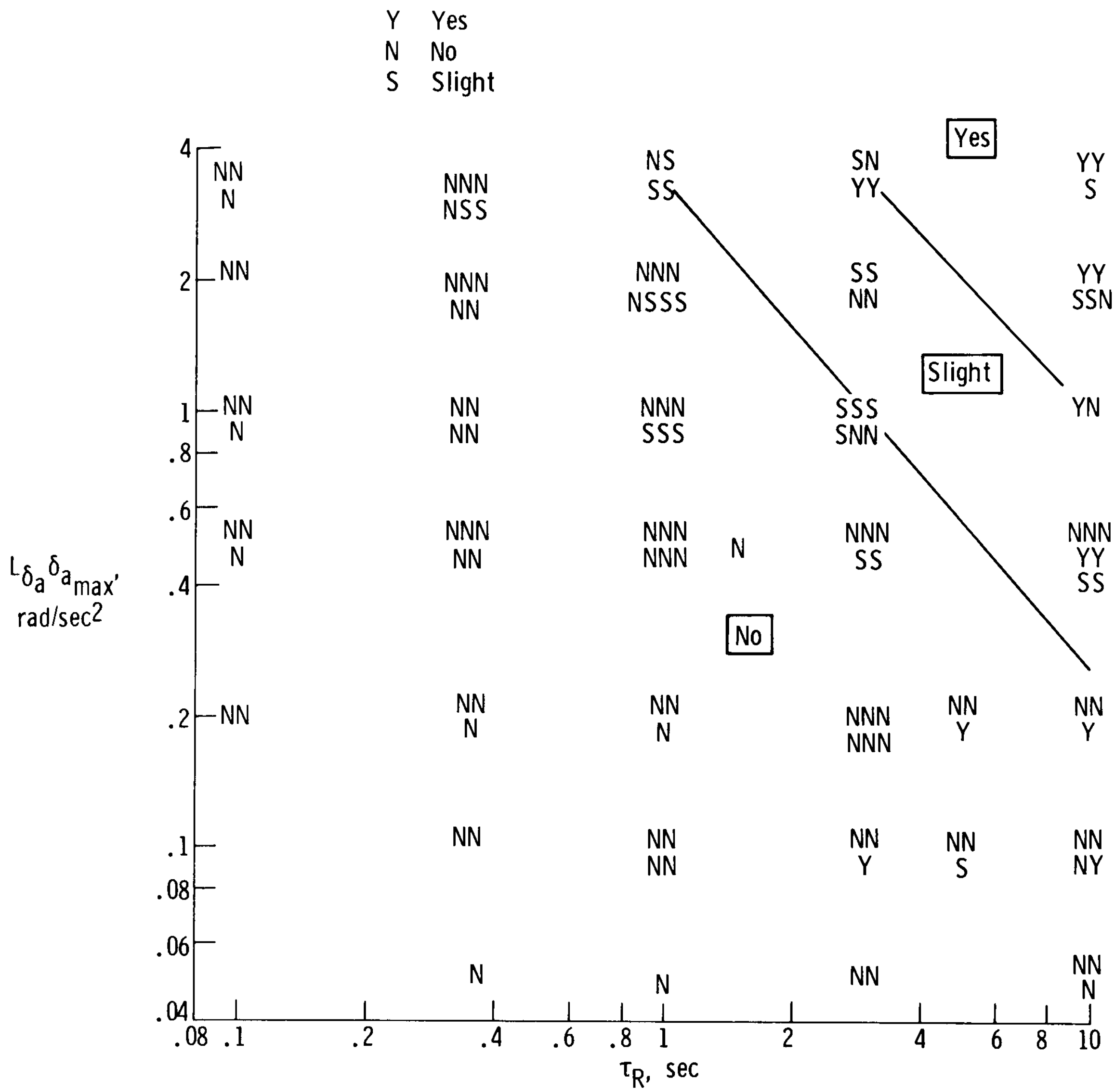


Figure 14. Summary of pilot comments concerning question G (table 1): Any tendency to overcontrol or P. I. O. ?

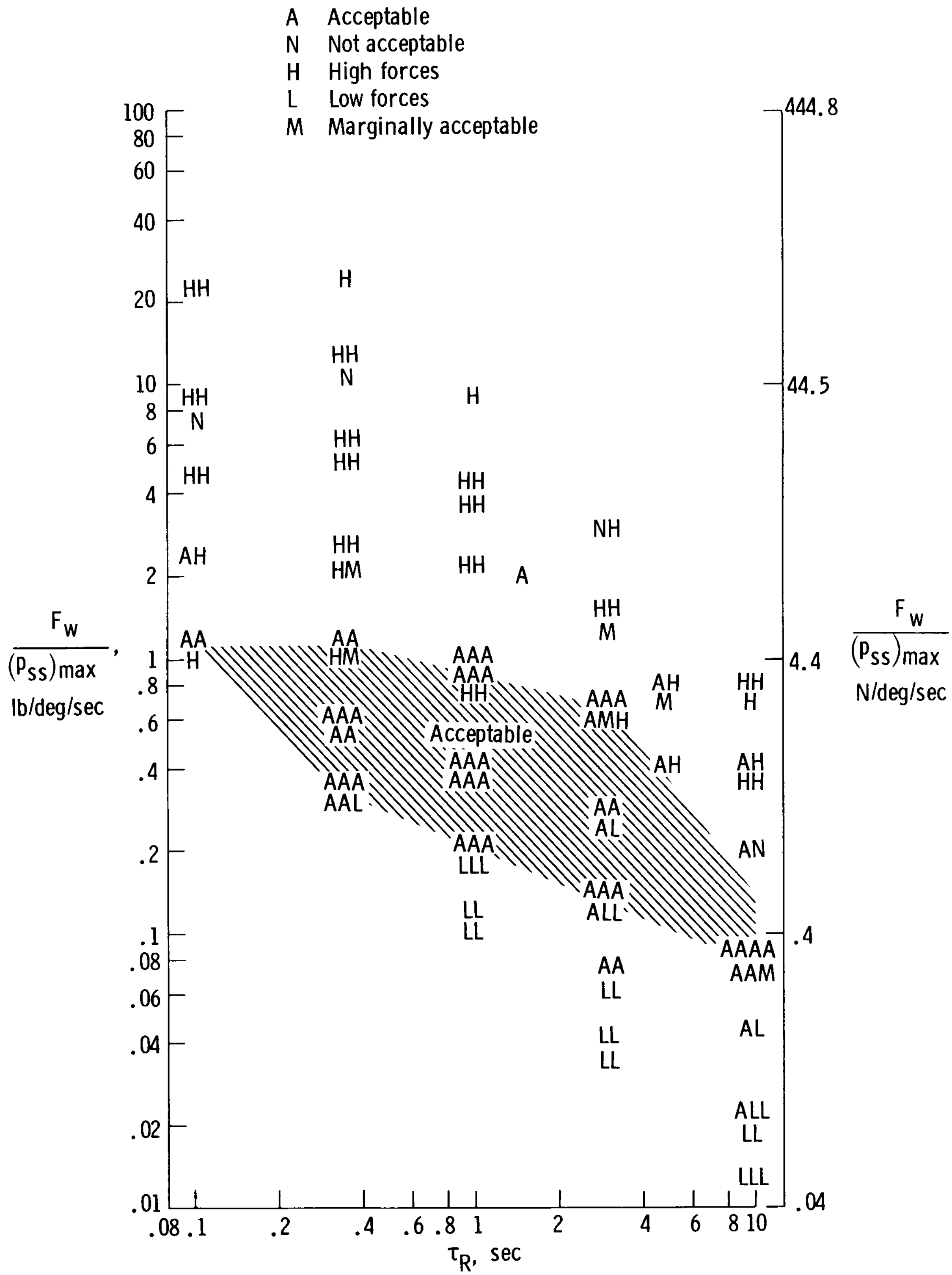


Figure 15. Summary of pilot comments concerning question J (table 1): Were the control-wheel deflection and force characteristics acceptable for a transport?

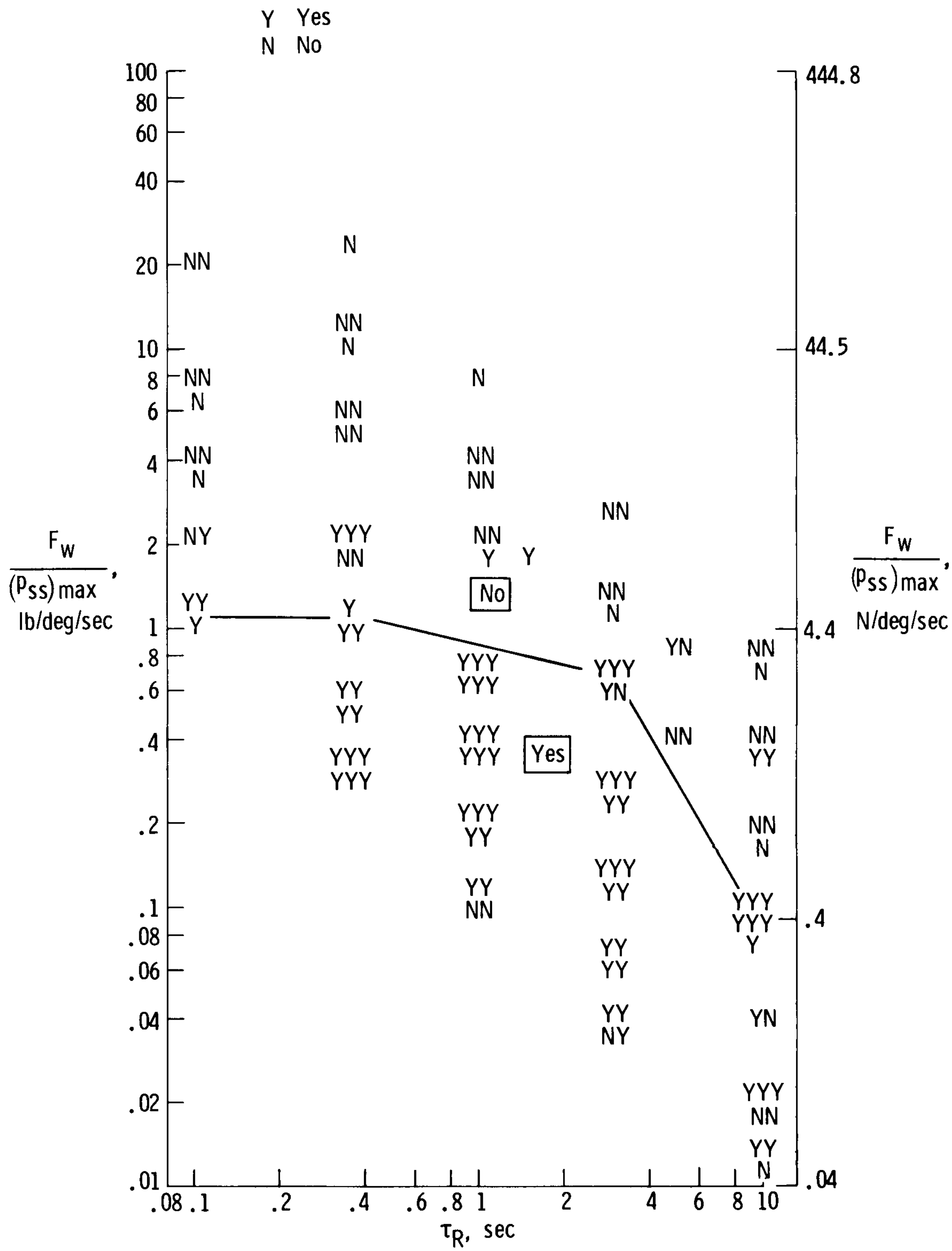


Figure 16. Summary of pilot comments concerning question L (table 1): Can the airplane be maneuvered comfortably and safely with one hand?

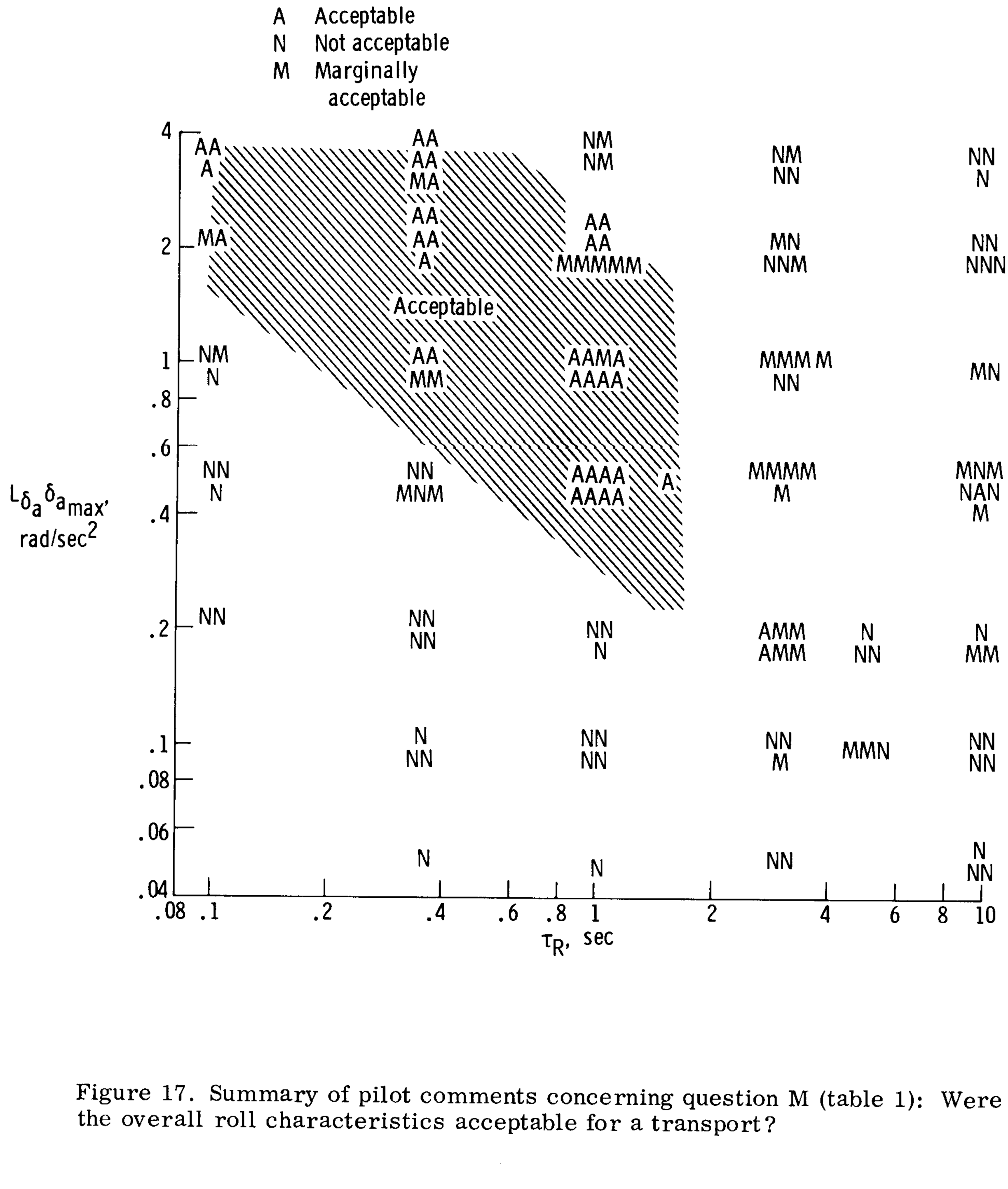
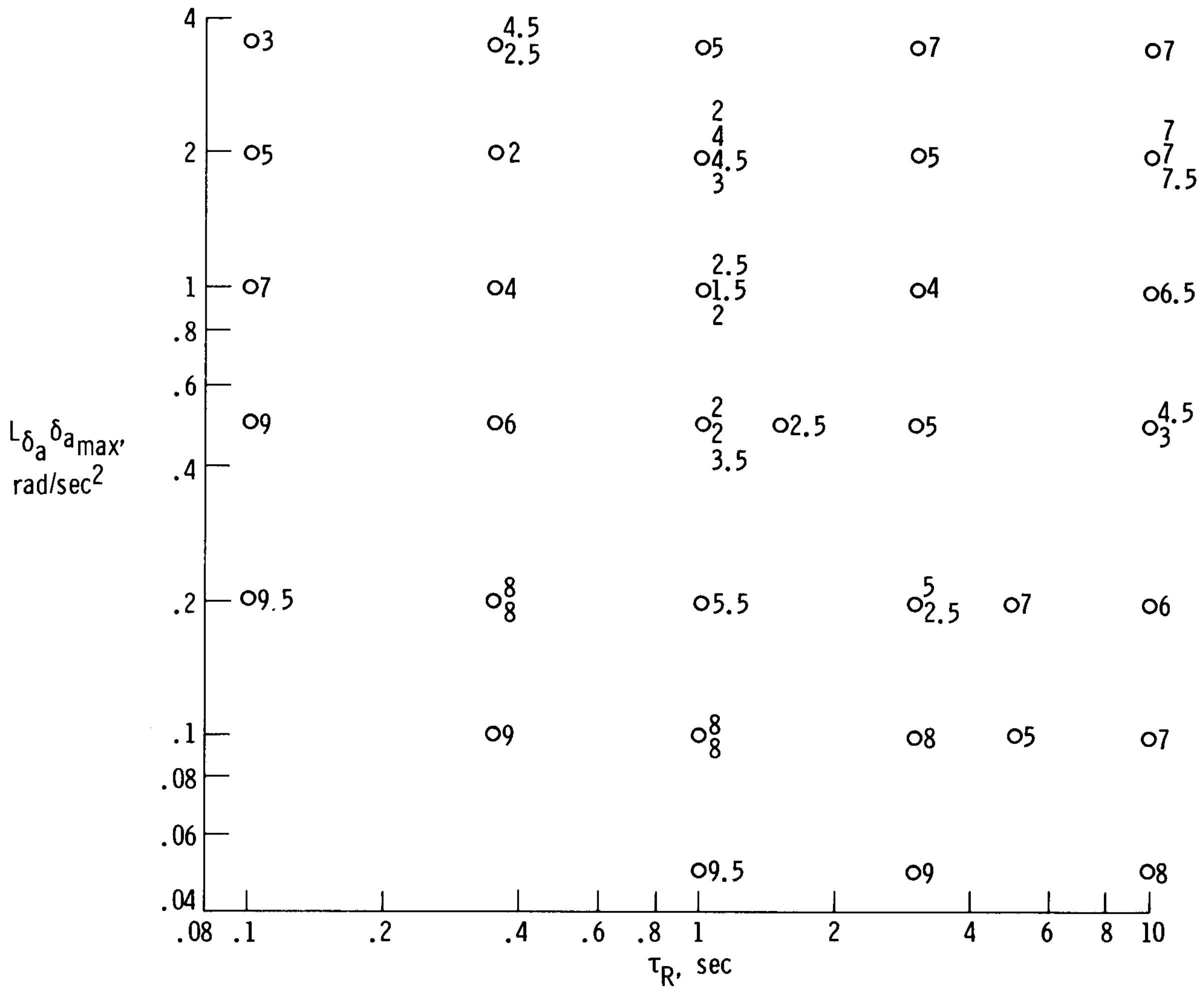
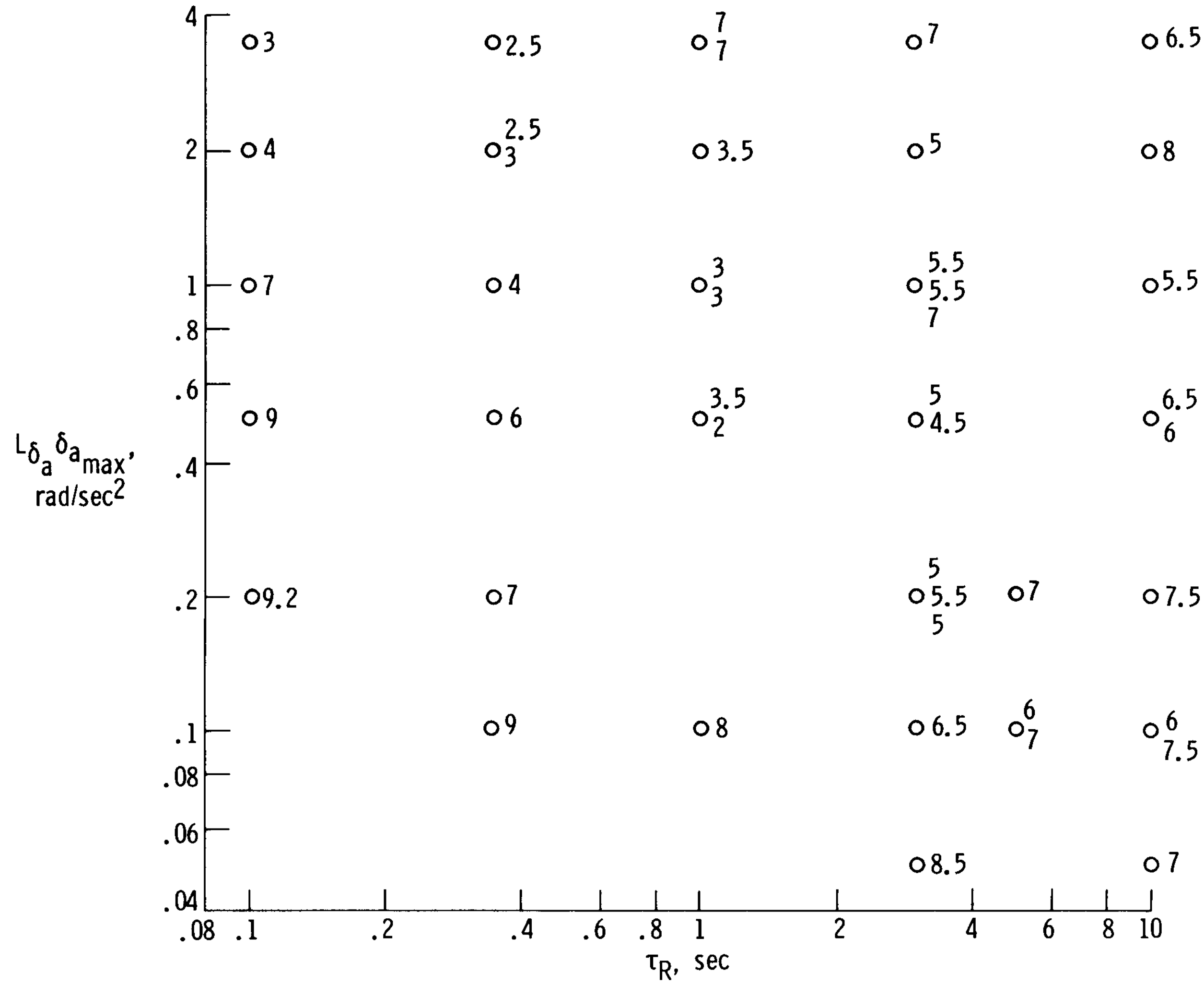


Figure 17. Summary of pilot comments concerning question M (table 1): Were the overall roll characteristics acceptable for a transport?



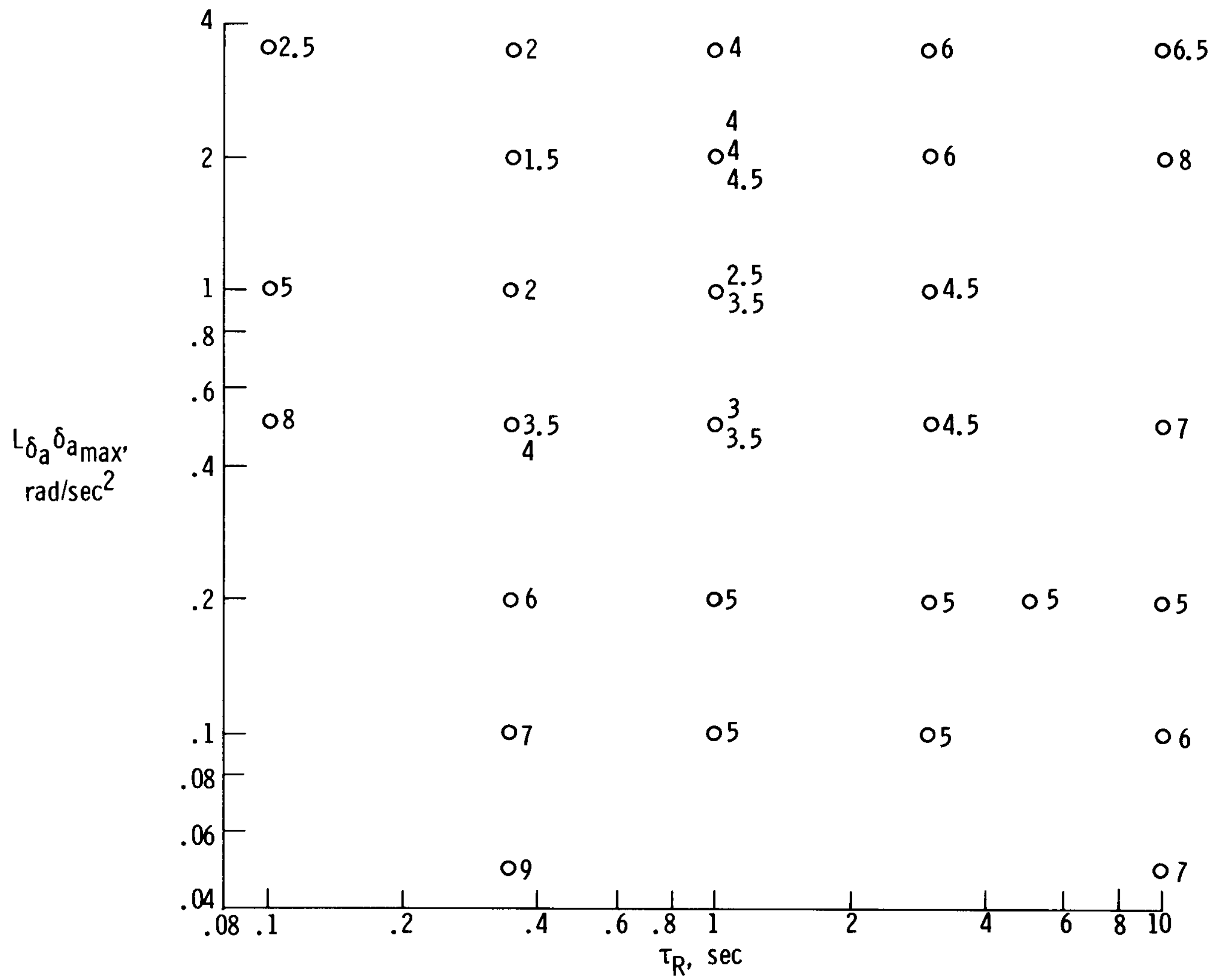
(a) Pilot A rating data.

Figure 18. Summary of individual pilot ratings of the roll characteristics investigated.



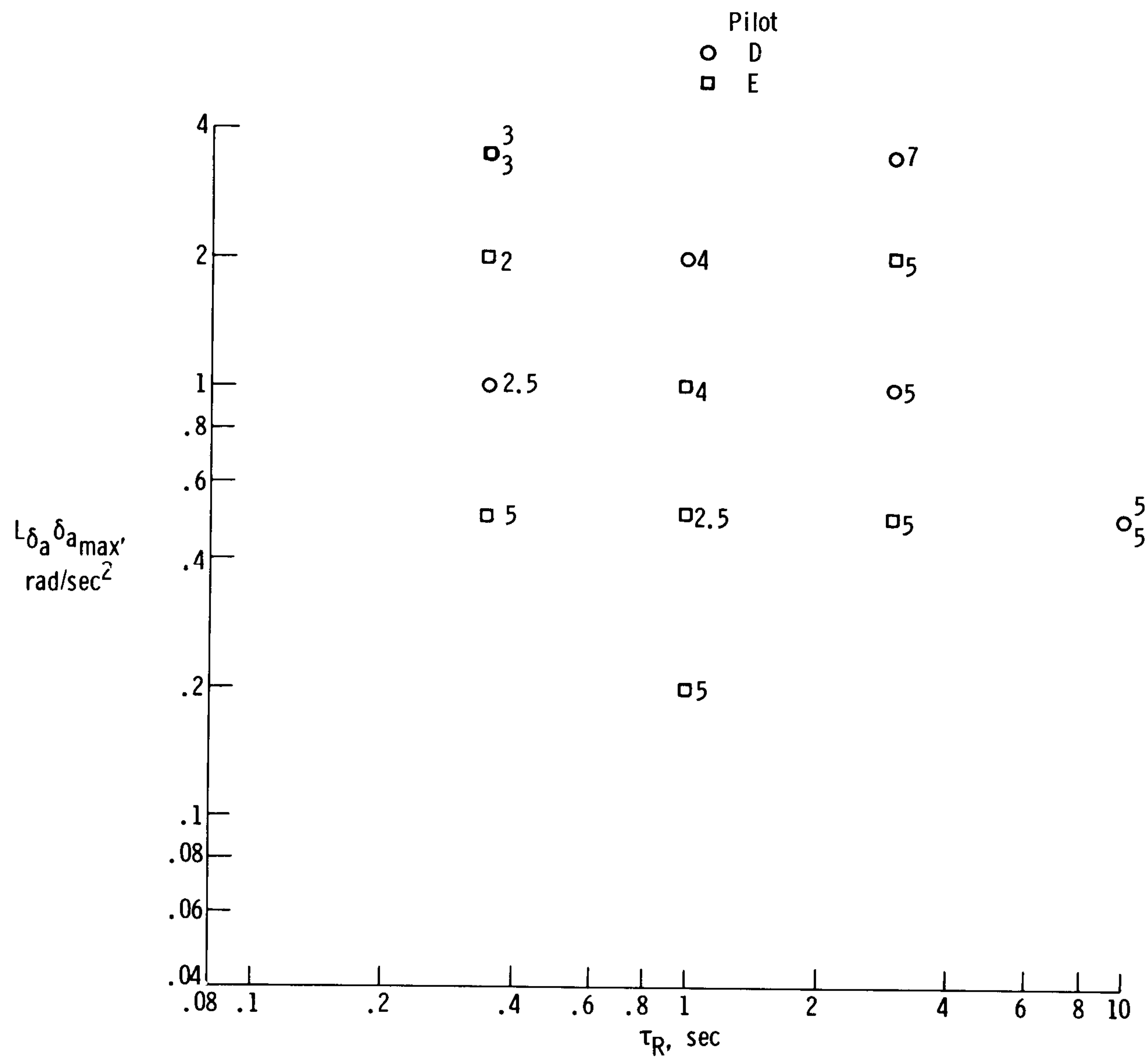
(b) Pilot B rating data.

Figure 18. Continued.



(c) Pilot C rating data.

Figure 18. Continued.



(d) Pilots D and E rating data.

Figure 18. Concluded.

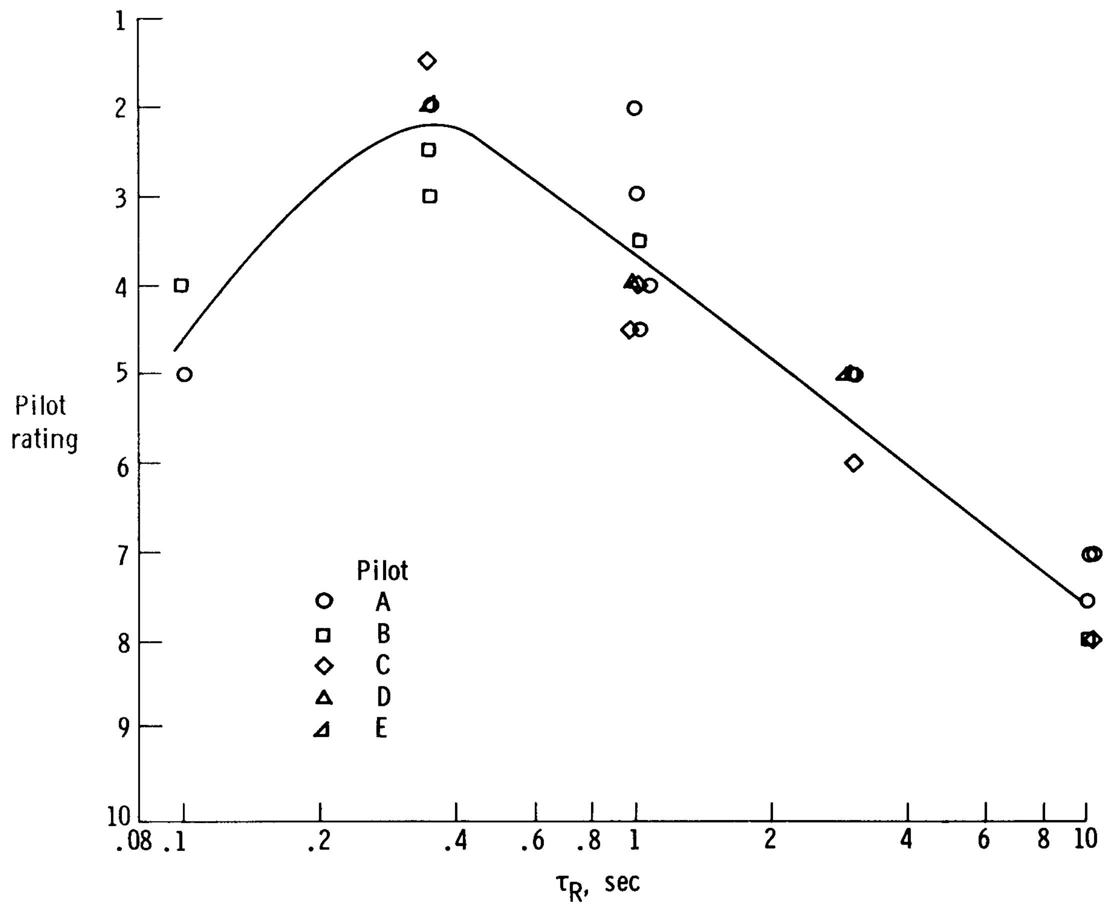


Figure 19. Determination of optimum τ_R for a roll-control effectiveness of $L_{\delta_a}\delta_{a_{max}} = 2.0$ rad/sec^2.

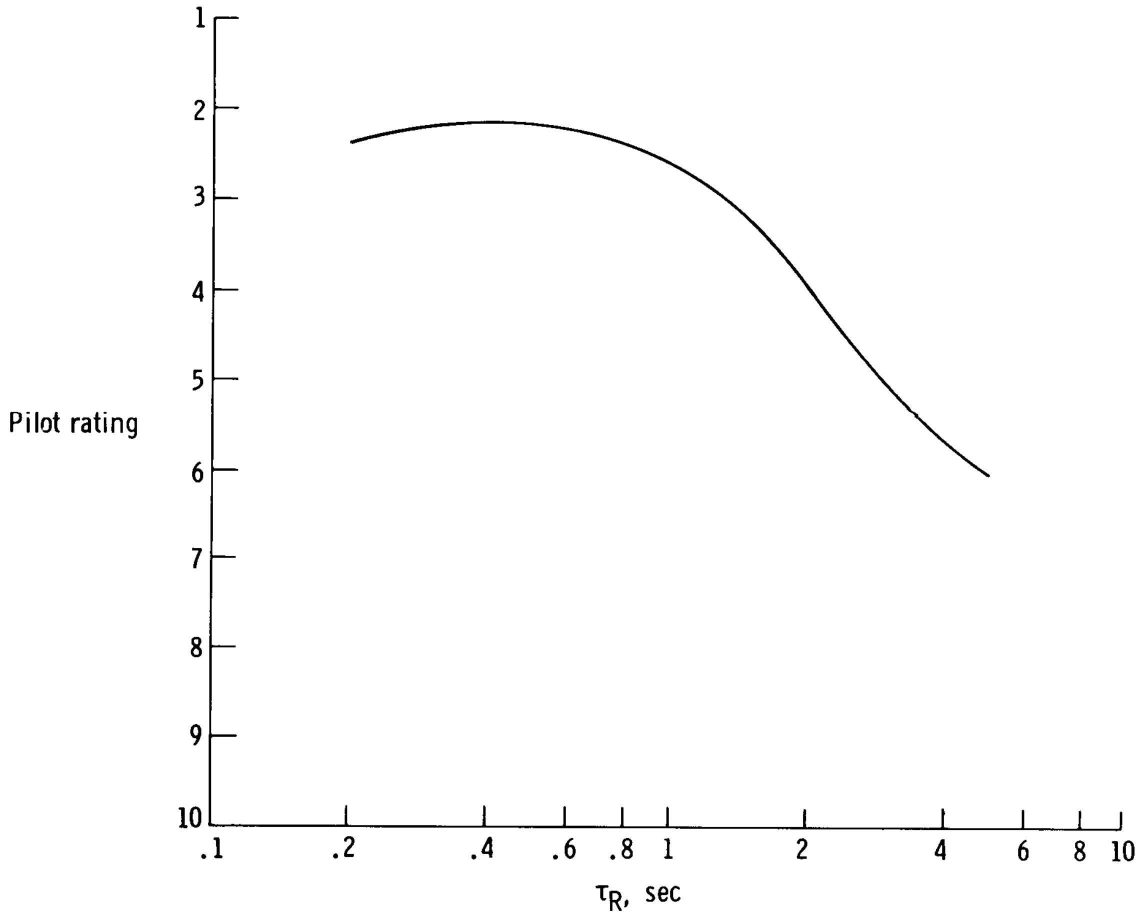


Figure 20. Roll time constant for optimum pilot rating. $L_{\delta_a}\delta_{a_{max}} = 0.1$ rad/sec^2 to 3.5 rad/sec^2.

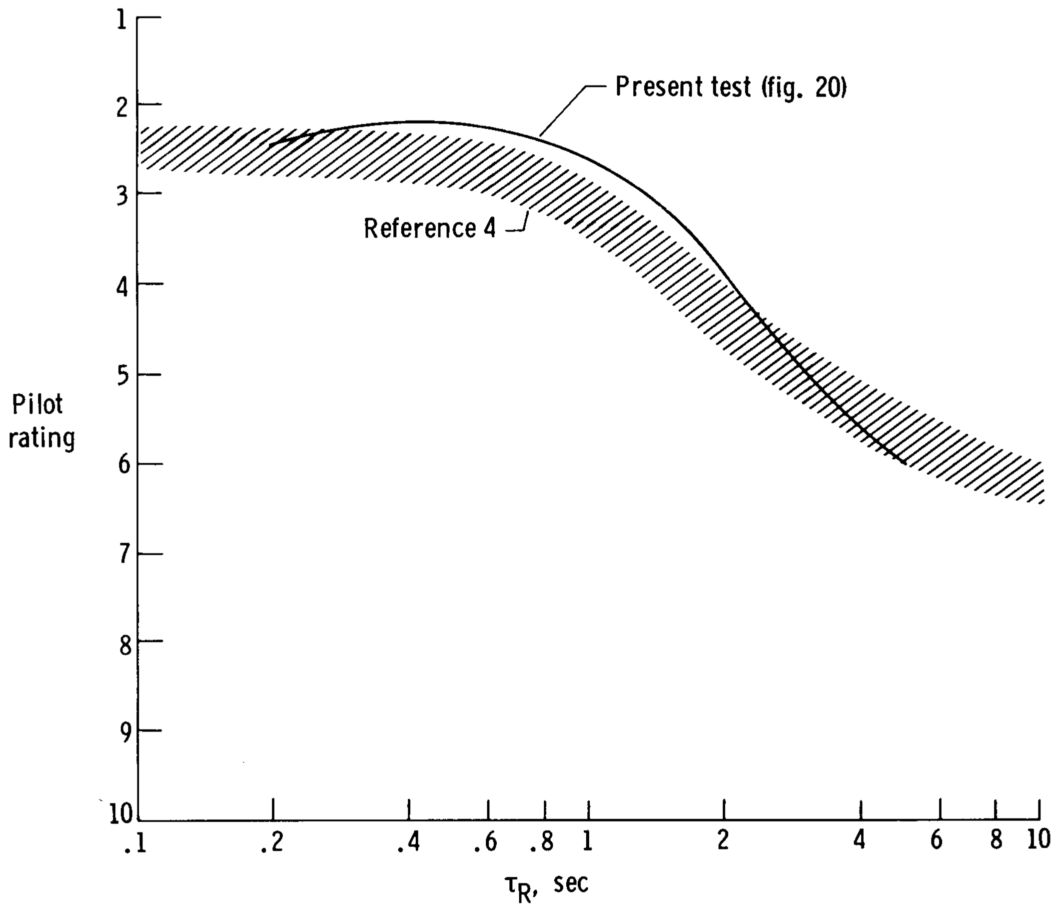


Figure 21. Comparison of present results for pilot rating of roll time constant with those of reference 4.

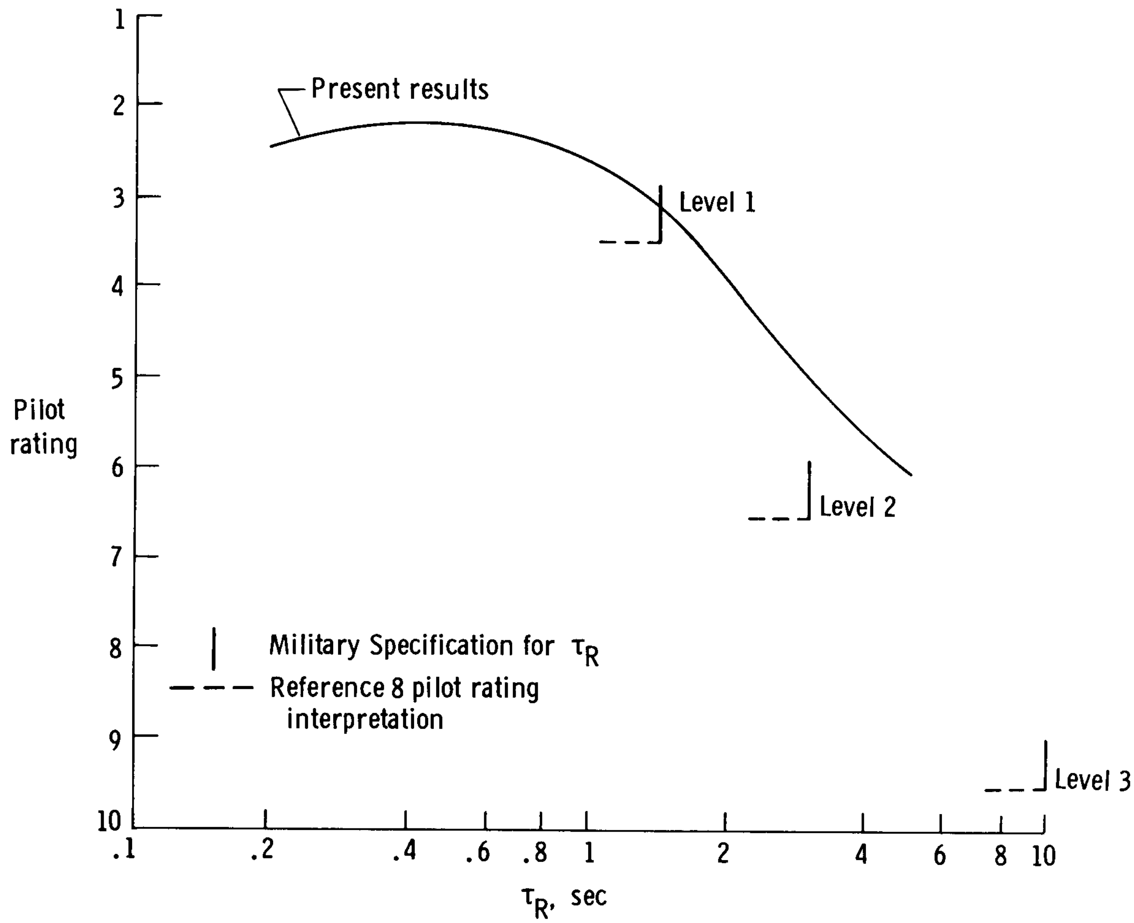


Figure 22. Comparison of the present test results and reference 8 interpretation of pilot rating for the military specification (ref. 16) for transport airplanes, class III, category B.

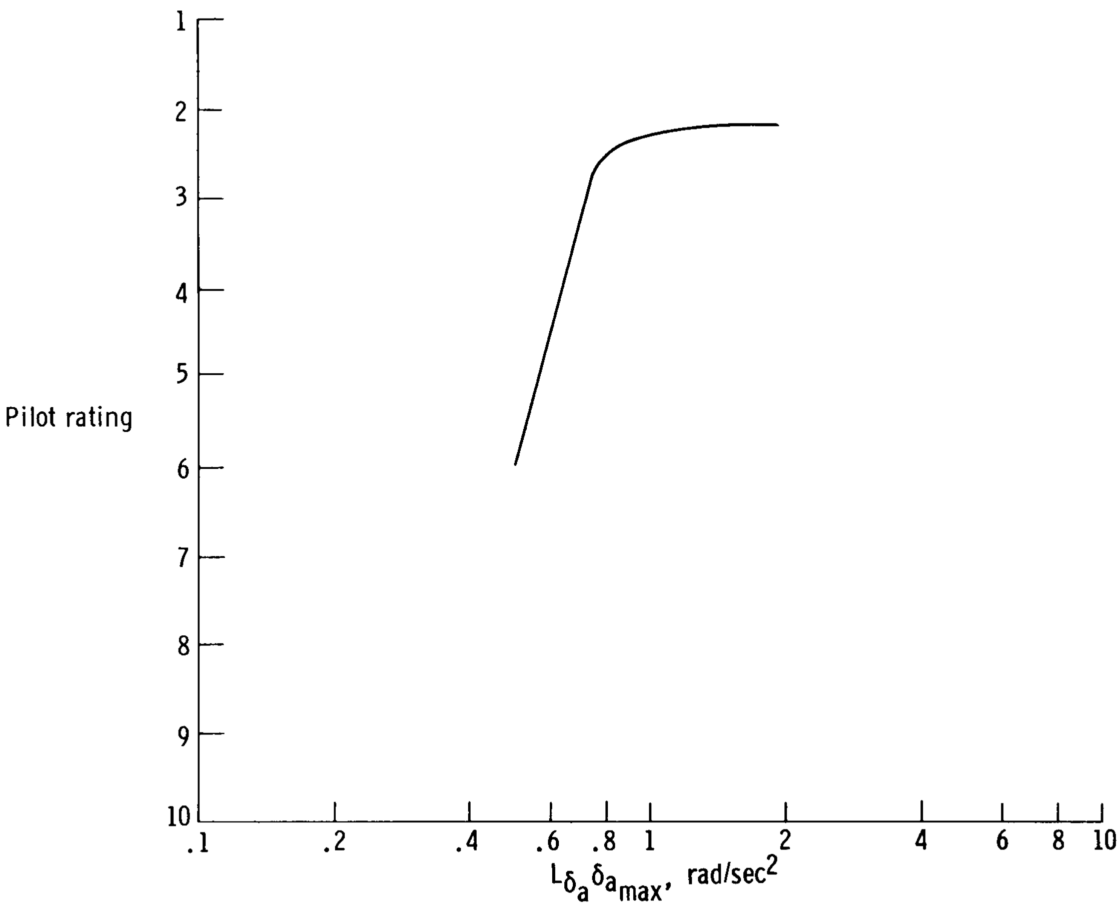


Figure 23. Roll-control effectiveness for optimum pilot rating for the range of roll time constants of 0. 35 to 10 sec.

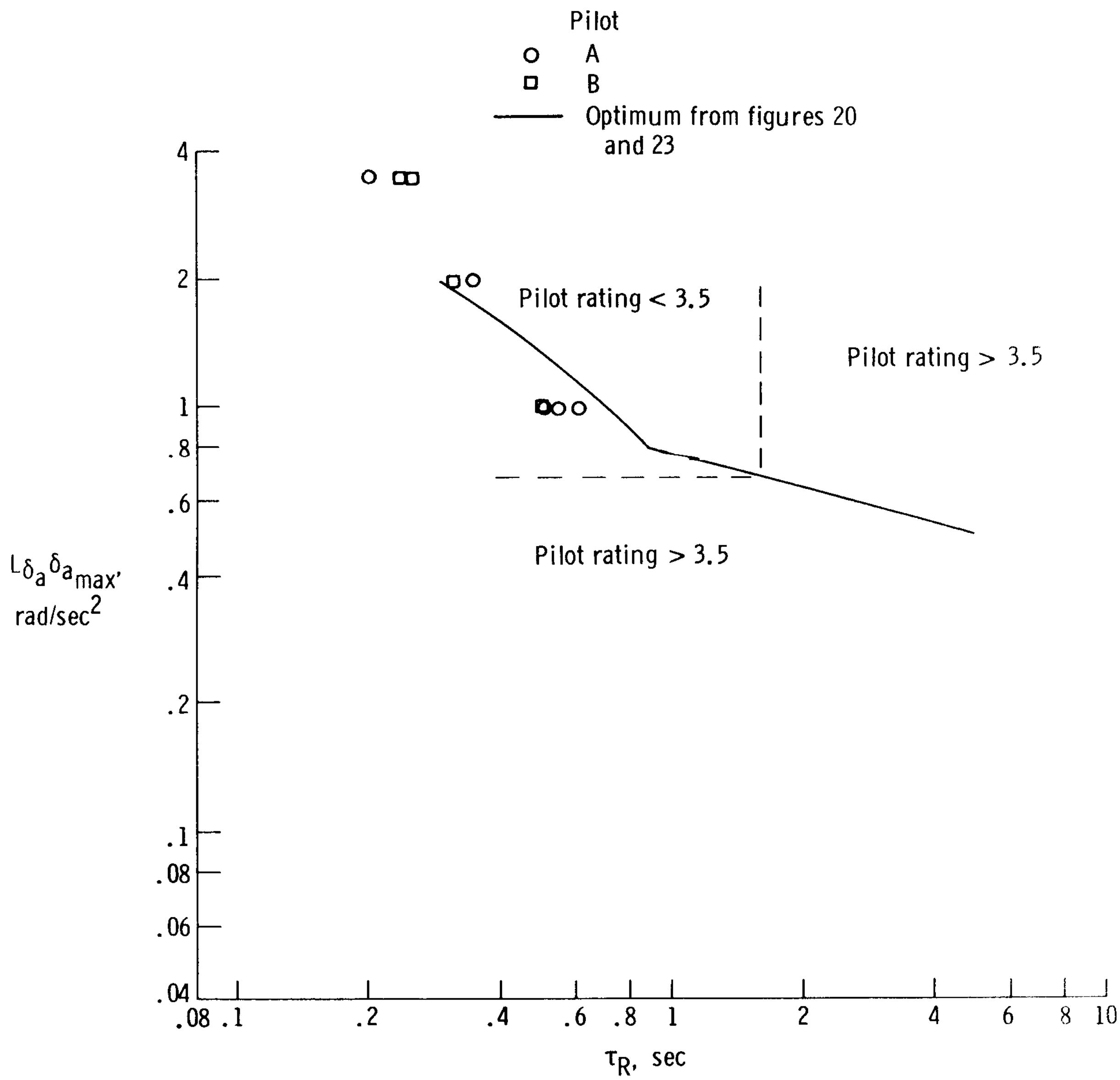


Figure 24. Comparison of roll characteristics for optimum pilot rating derived from all pilot rating data and obtained from pilots A and B selecting optimum characteristics.

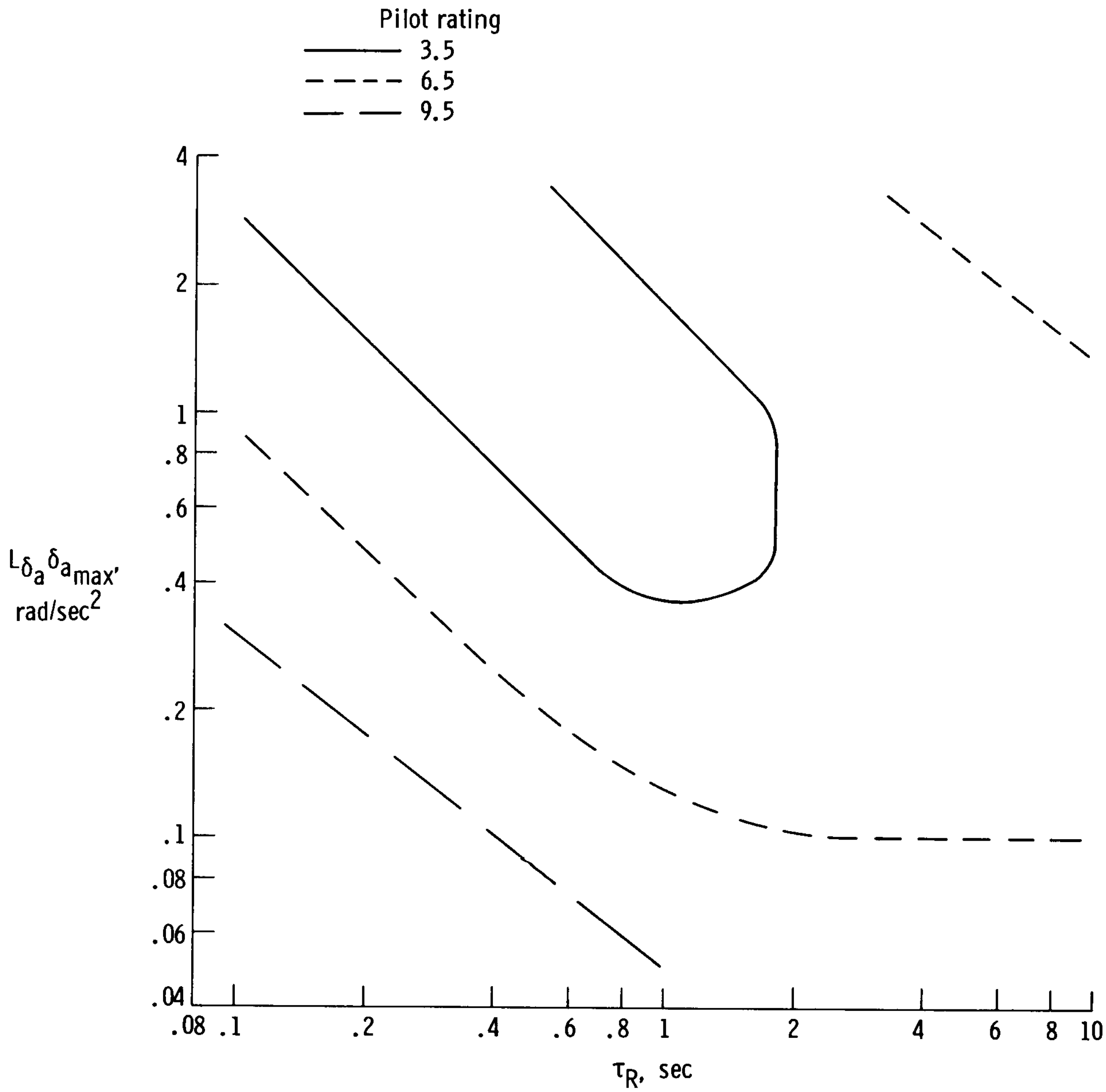


Figure 25. Regions of satisfactory, unsatisfactory, and unacceptable (table 2) roll characteristics indicated by the present study.

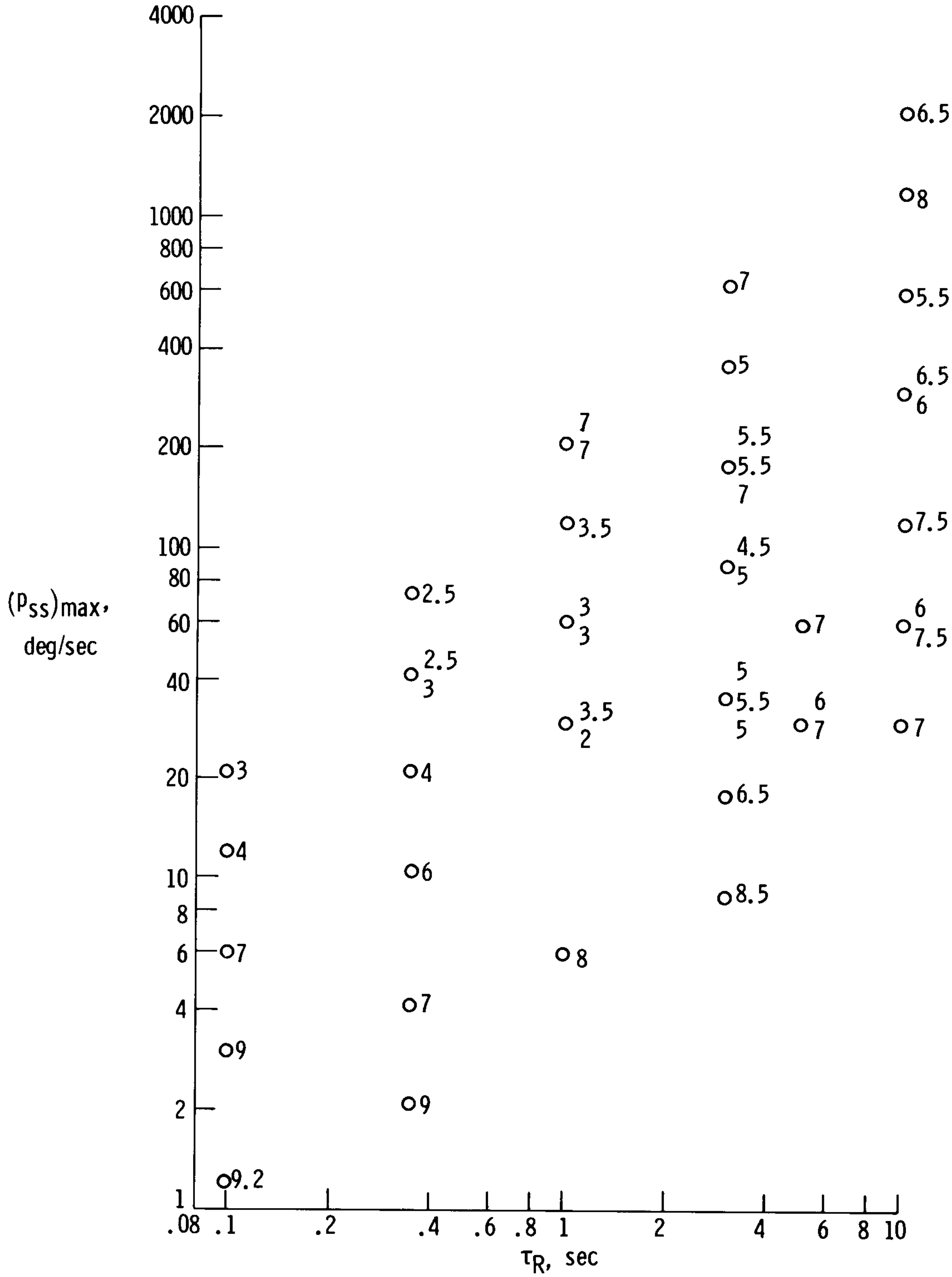


Figure 26. Pilot B ratings as a function of roll rate and time constant.

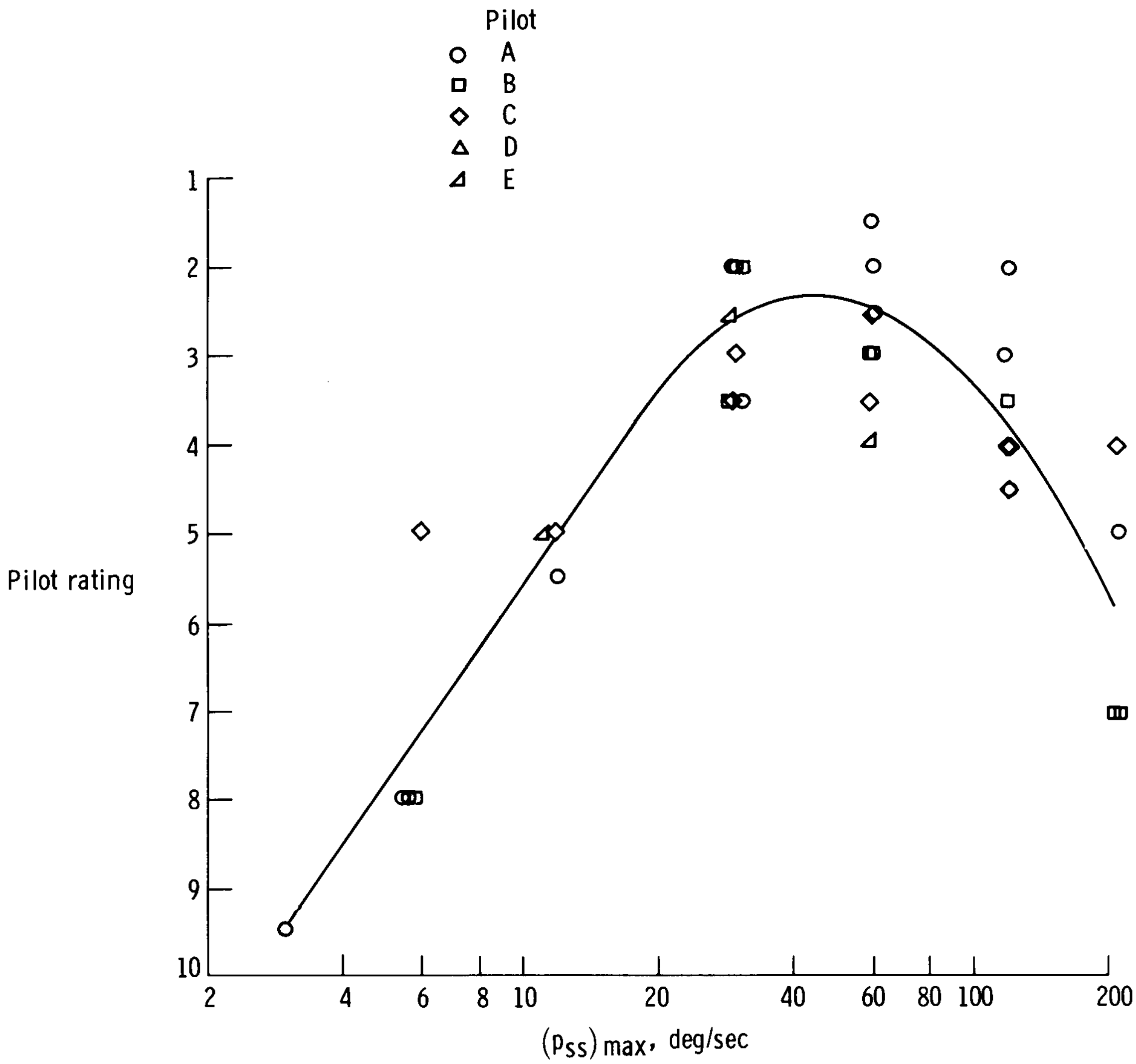


Figure 27. Determination of optimum steady-state roll rate for $\tau_R = 1.0$ sec.

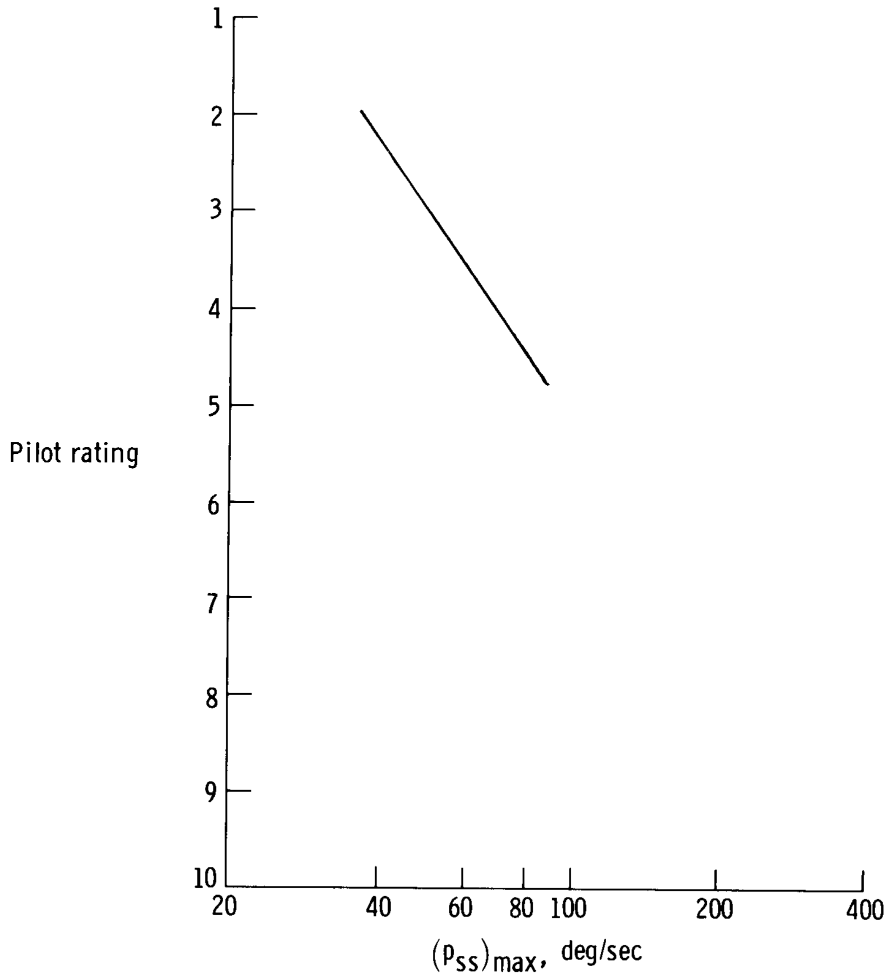


Figure 28. Steady-state roll rate for optimum pilot rating. $\tau_R = 0.35$ to 3 sec.

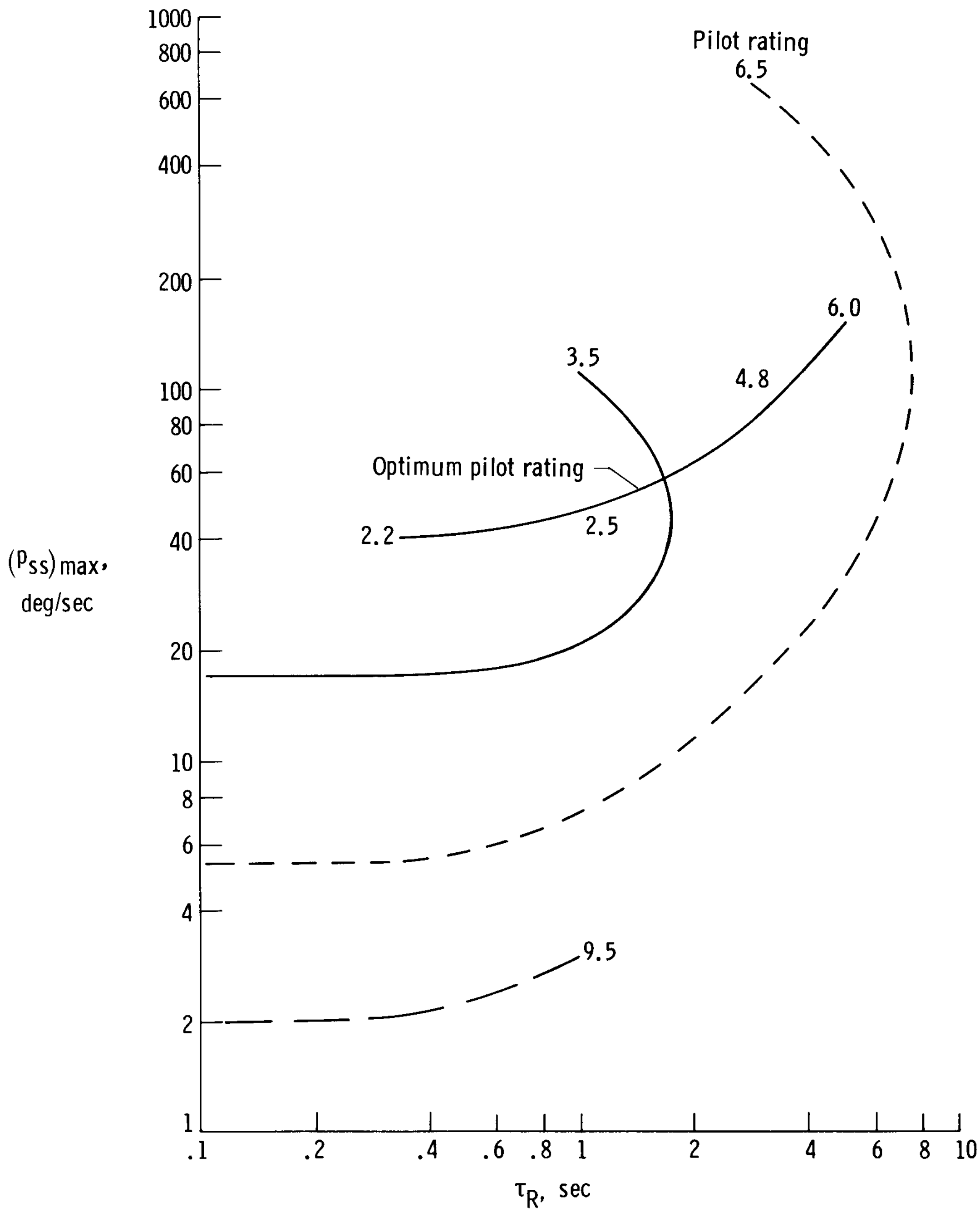
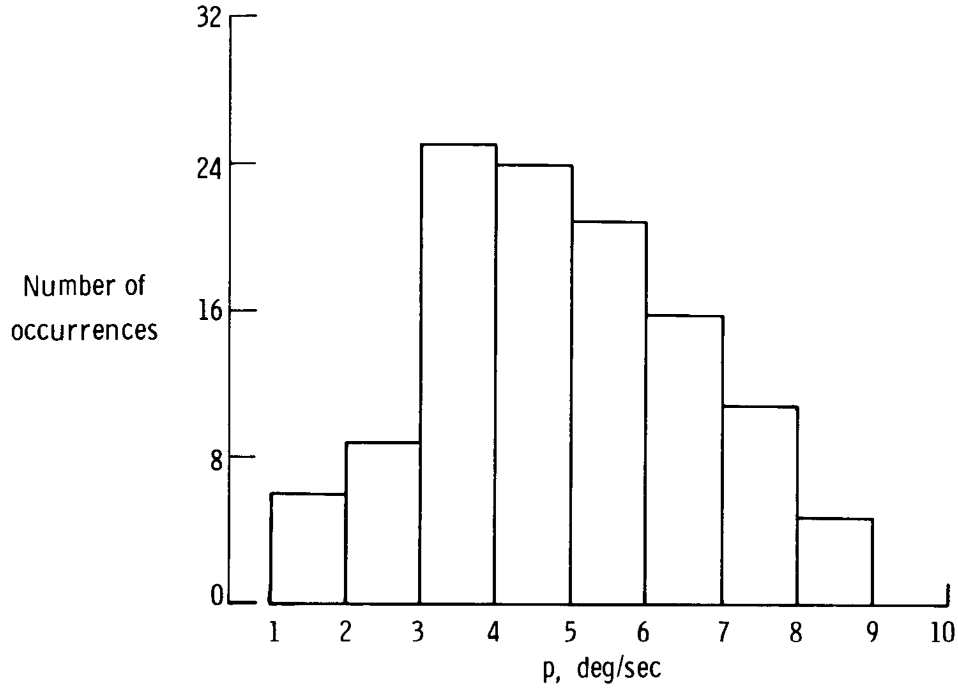
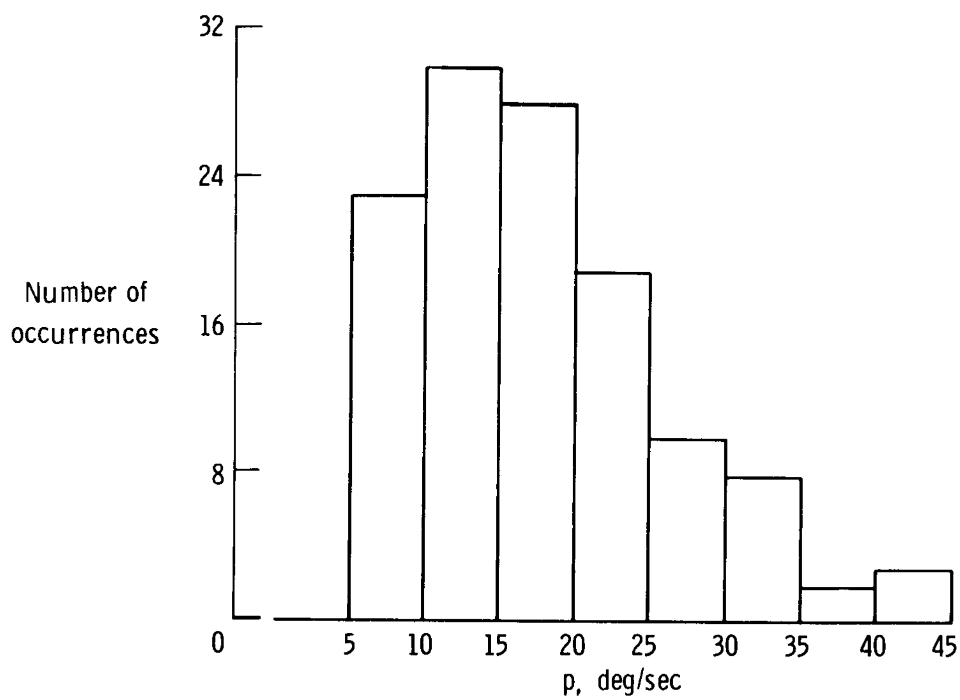


Figure 29. Regions of satisfactory, unsatisfactory, and unacceptable (table 2) roll rate and damping.



(a) Normal roll rate; average, 5.3 deg/sec; standard deviation, 2.1 deg/sec.



(b) Fast roll rate; average, 17.3 deg/sec; standard deviation, 8.9 deg/sec.

Figure 30. Distribution of maximum roll rate used by the pilots when demonstrating normal and fast (maximum rate needed) roll rate for maneuvering transport aircraft.

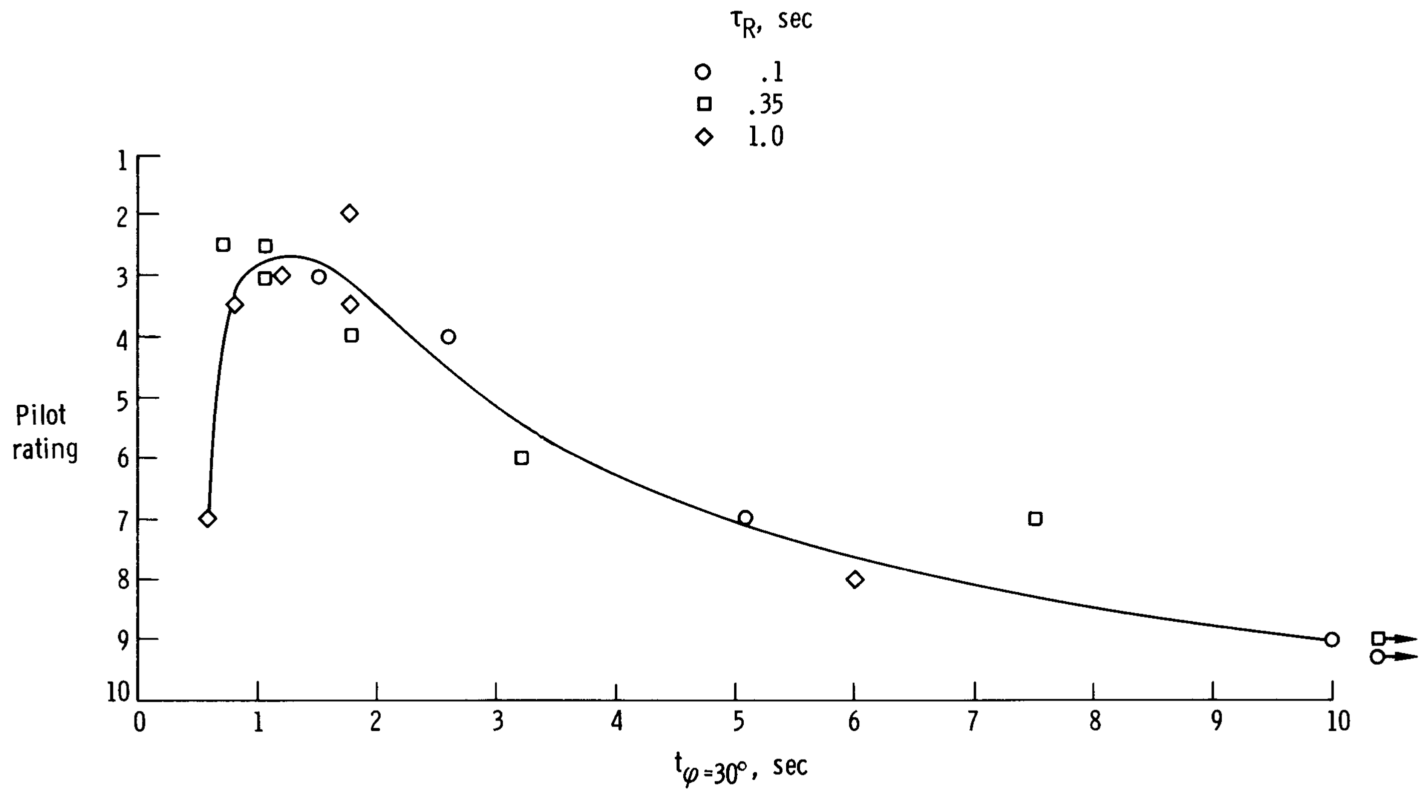


Figure 31. Determination of the optimum time to bank 30° from pilot B ratings. Only satisfactory time-constant data used.

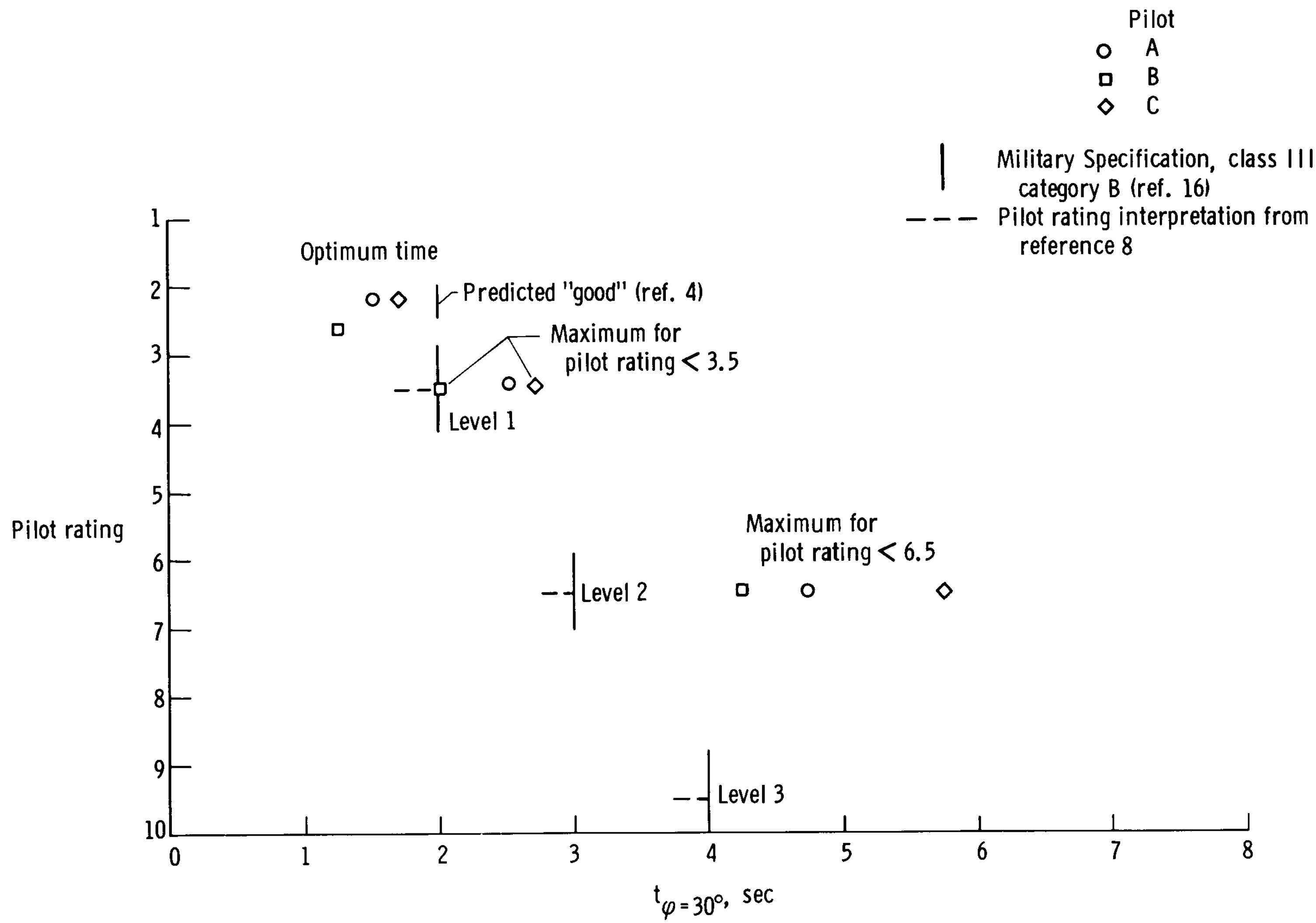
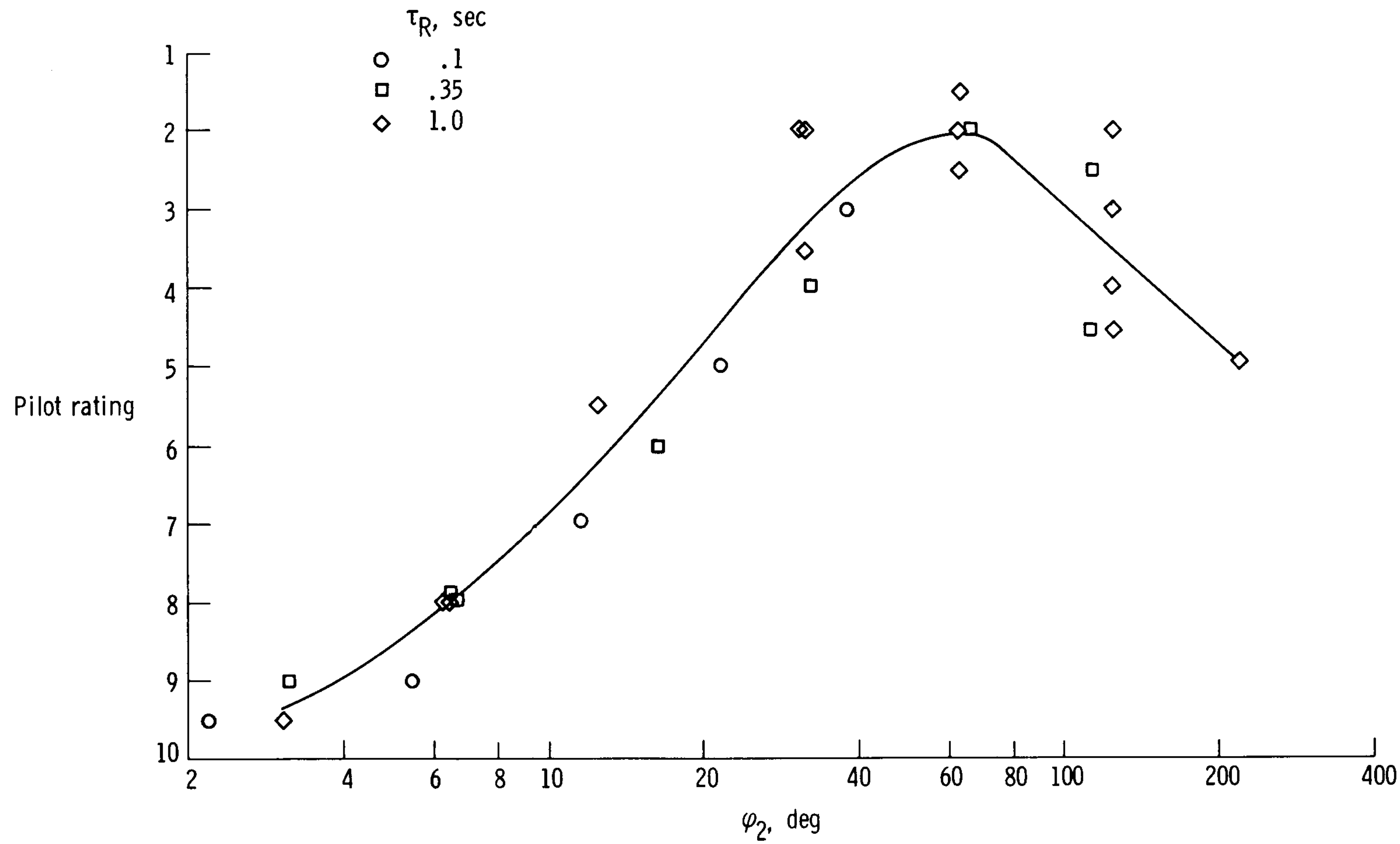
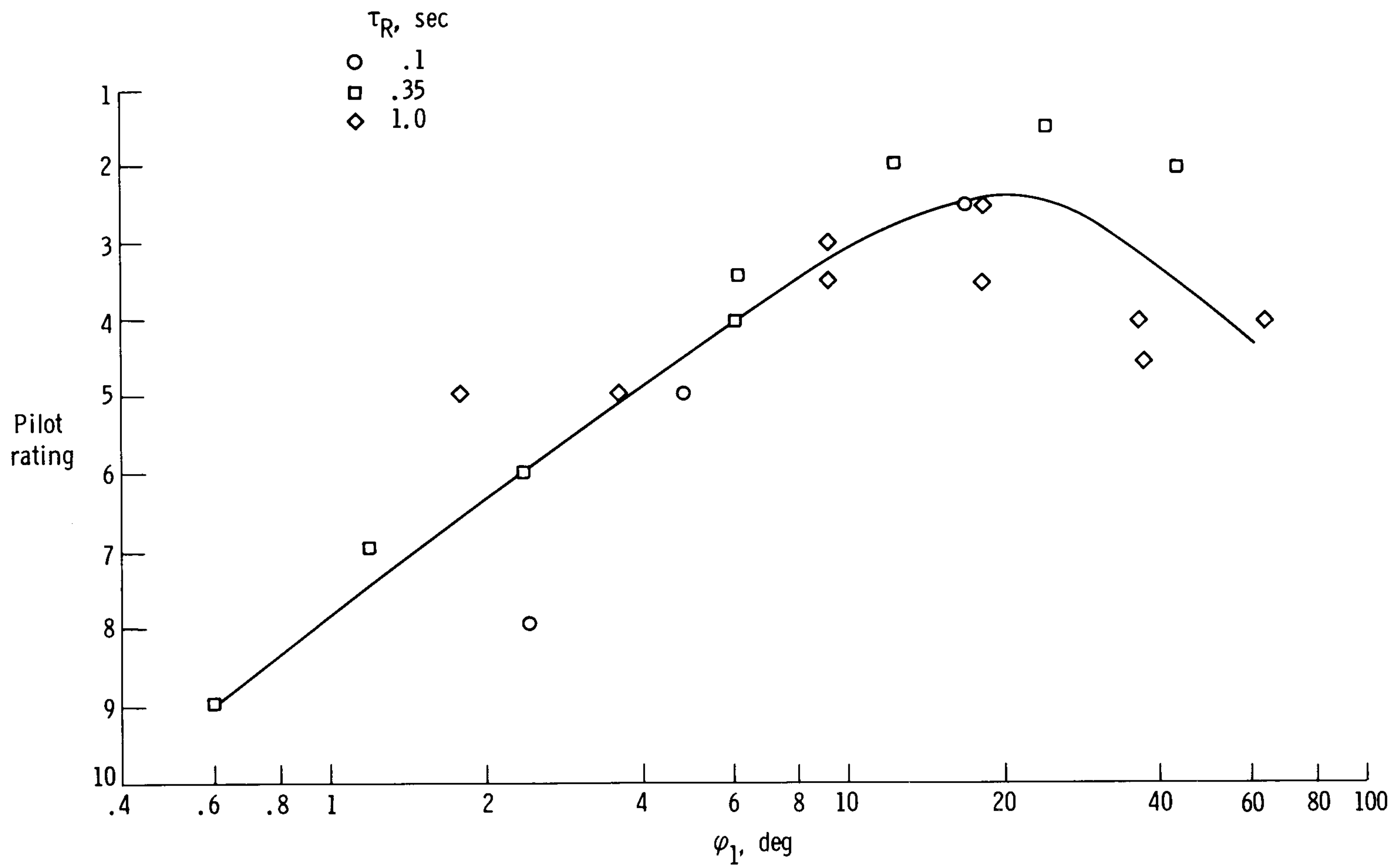


Figure 32. Comparison of optimum, satisfactory, unsatisfactory, and unacceptable time to bank 30° with reference 4, 16, and 8 results.



(a) Bank-angle change in 2 seconds. Pilot A.

Figure 33. Determination of optimum bank-angle change in a given time.



(b) Bank-angle change in 1 second. Pilot C.

Figure 33. Concluded.

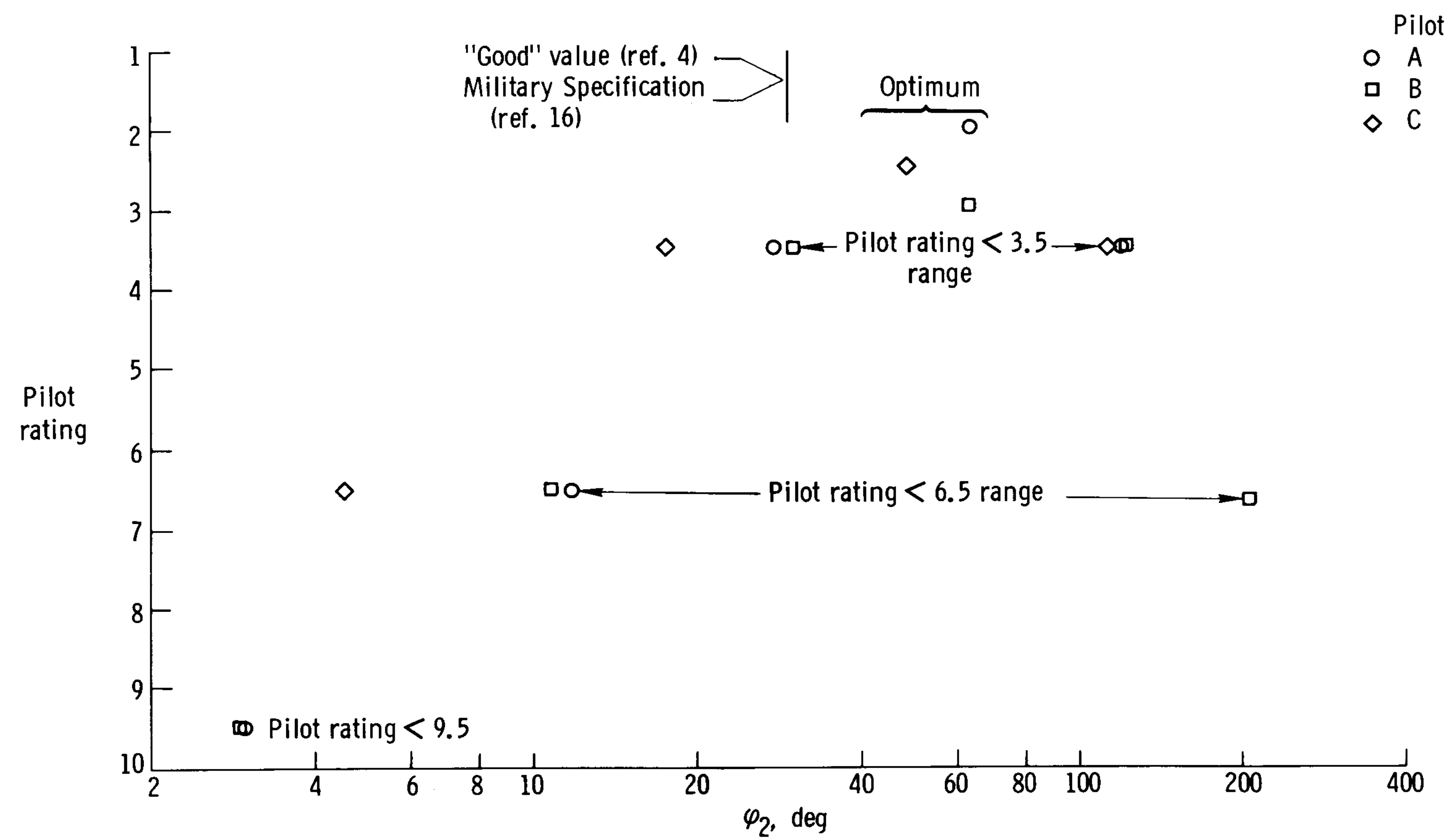


Figure 34. Bank-angle change in 2 seconds rated optimum, satisfactory, unsatisfactory, and unacceptable by program pilots and comparisons with referenced results.

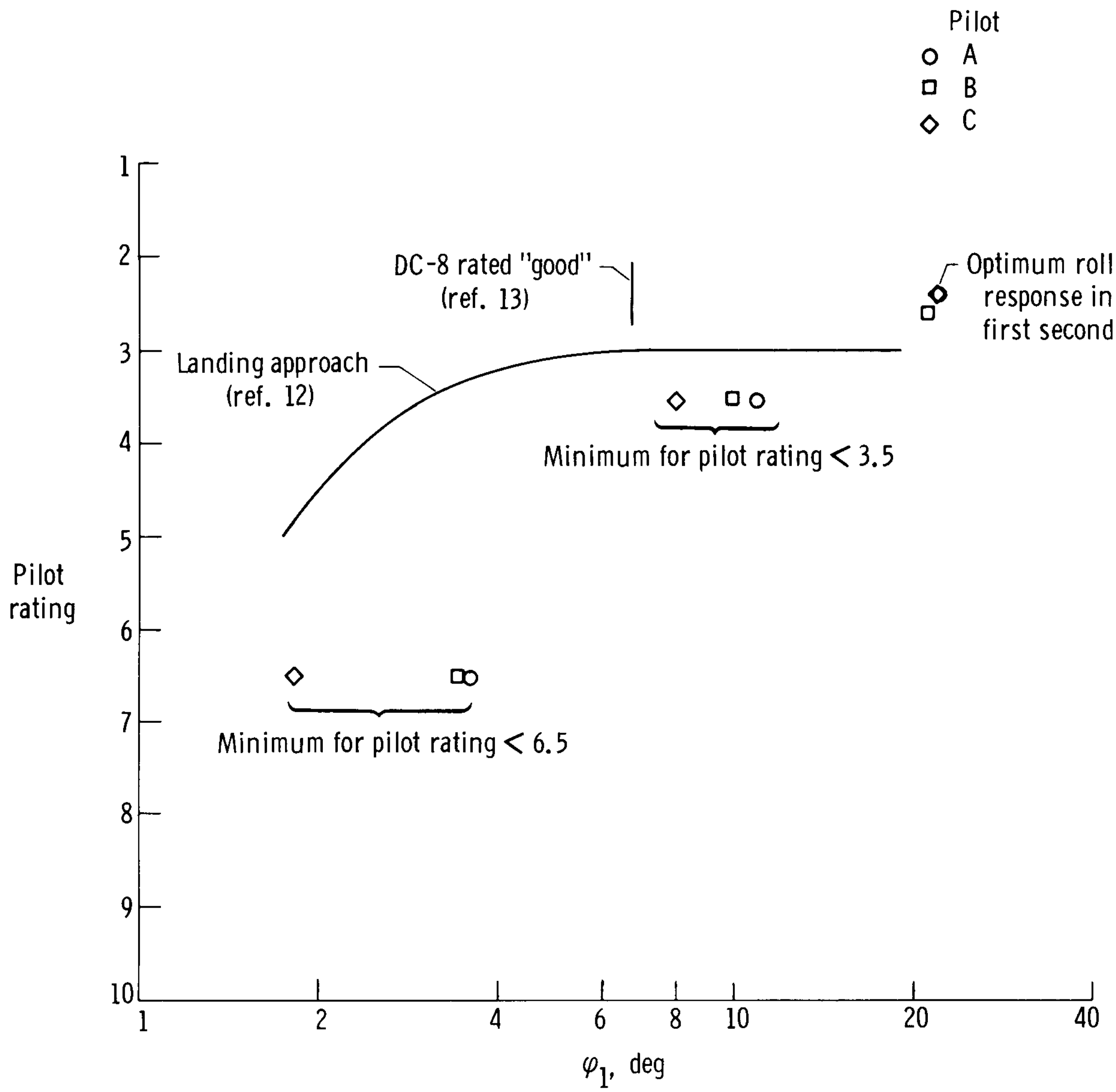


Figure 35. Bank-angle change in 1 second for optimum, satisfactory, and unsatisfactory ratings by program pilots and comparisons with referenced results.

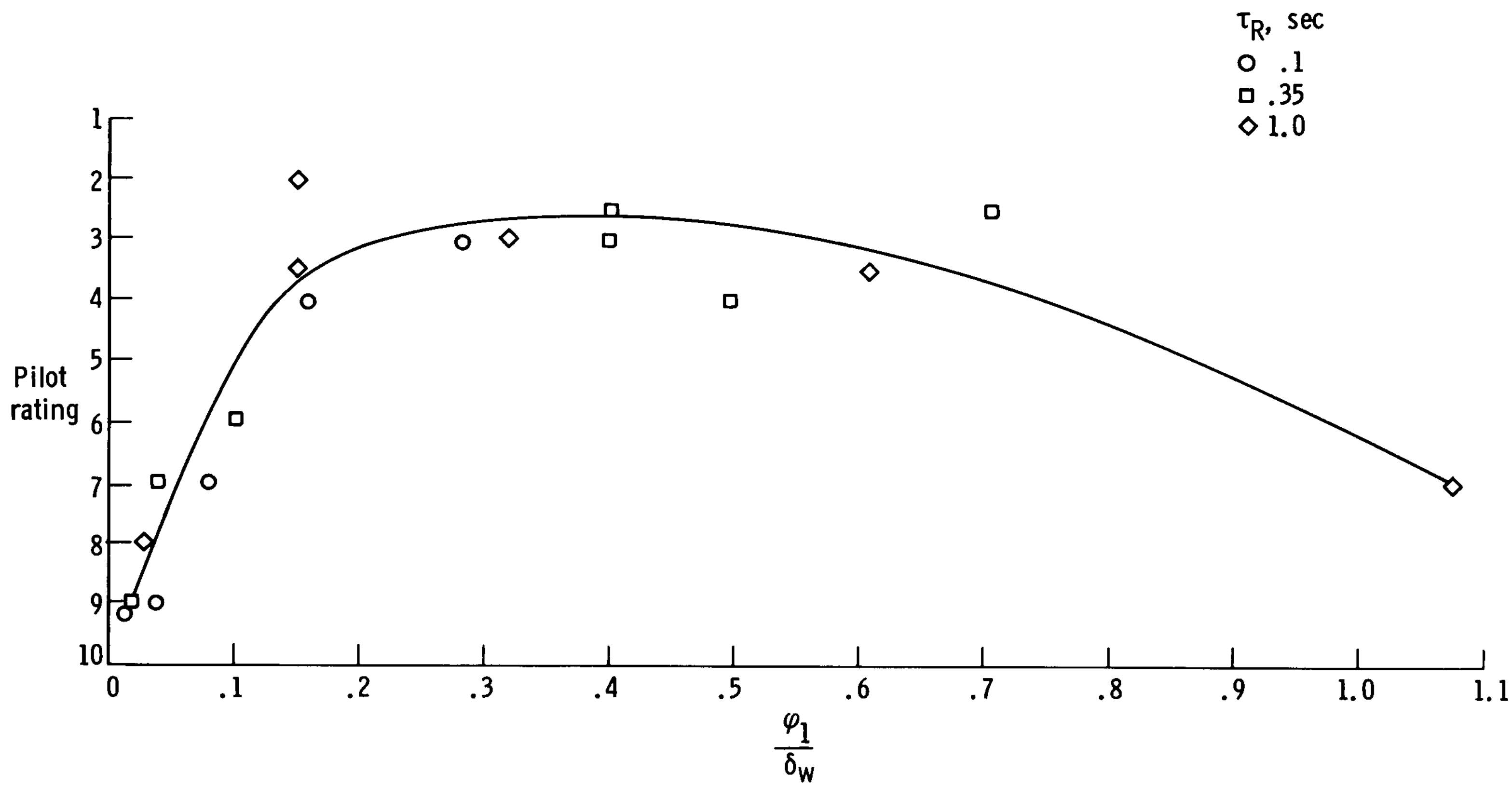


Figure 36. Determination of optimum roll-control sensitivity from pilot B ratings $\left(\frac{\varphi_1}{\delta_W}\right.$ may be converted to $\frac{\varphi_1}{F_W}$ by multiplying by 2.5$\left.\right)$.

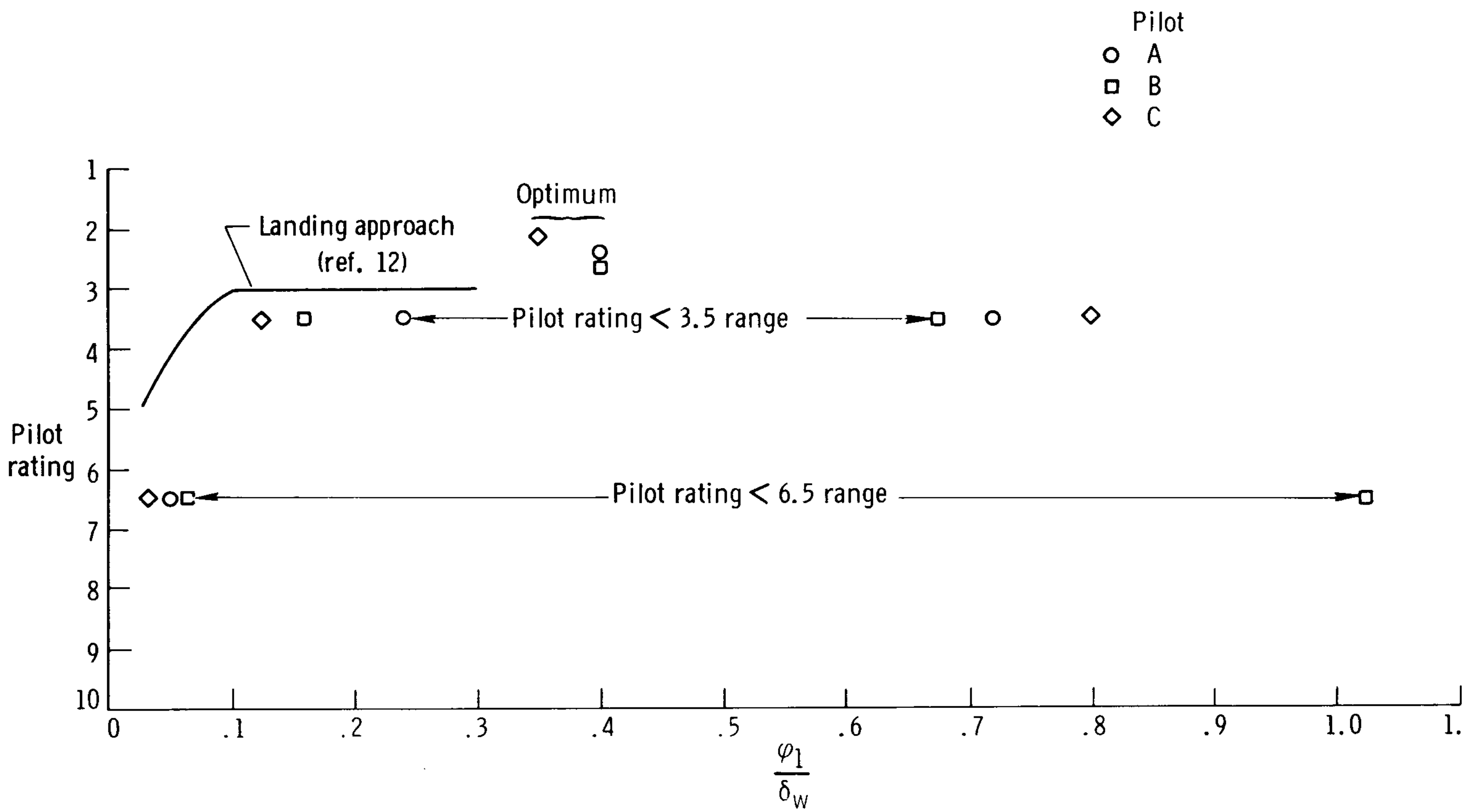
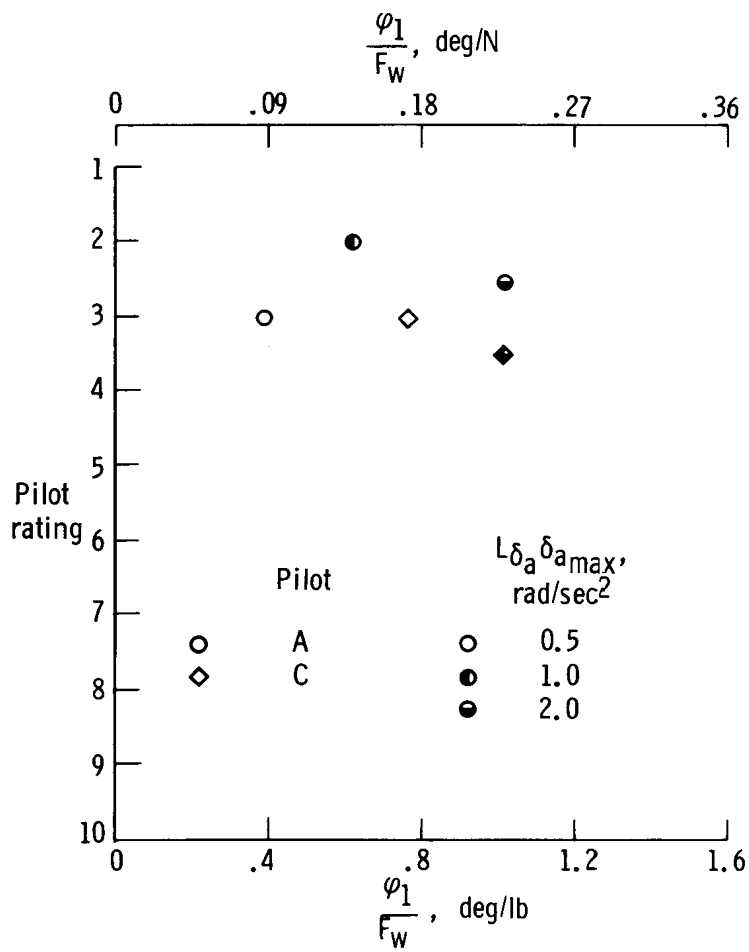
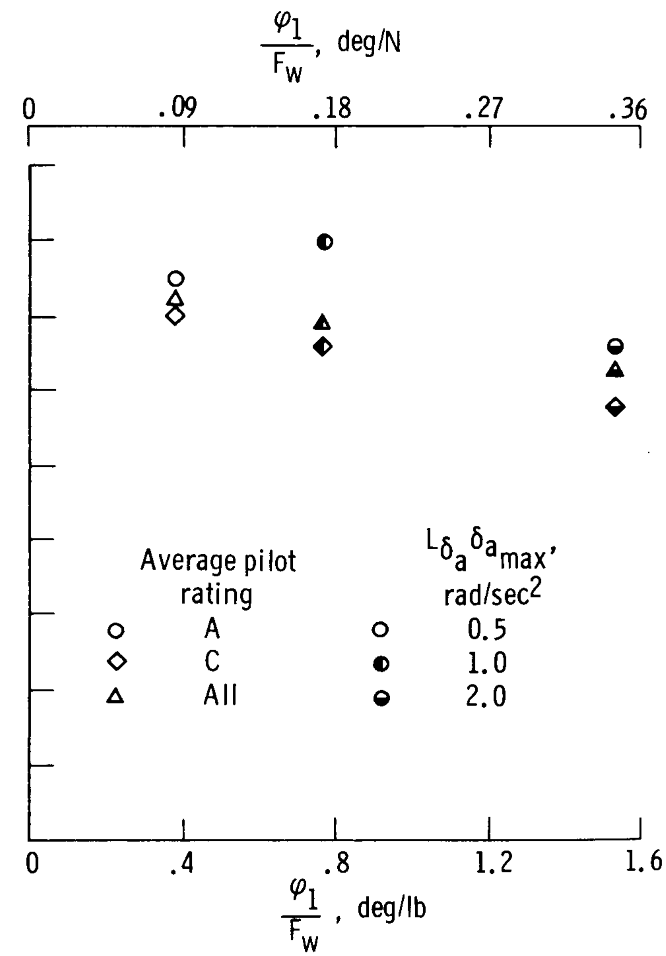


Figure 37. Program pilots' evaluations of faired results of roll-control sensitivity for transport aircraft $\left(\frac{\varphi_1}{\delta_w}\right.$ may be converted to $\frac{\varphi_1}{F_w}$ by multiplying by $\left.2.5\right)$.

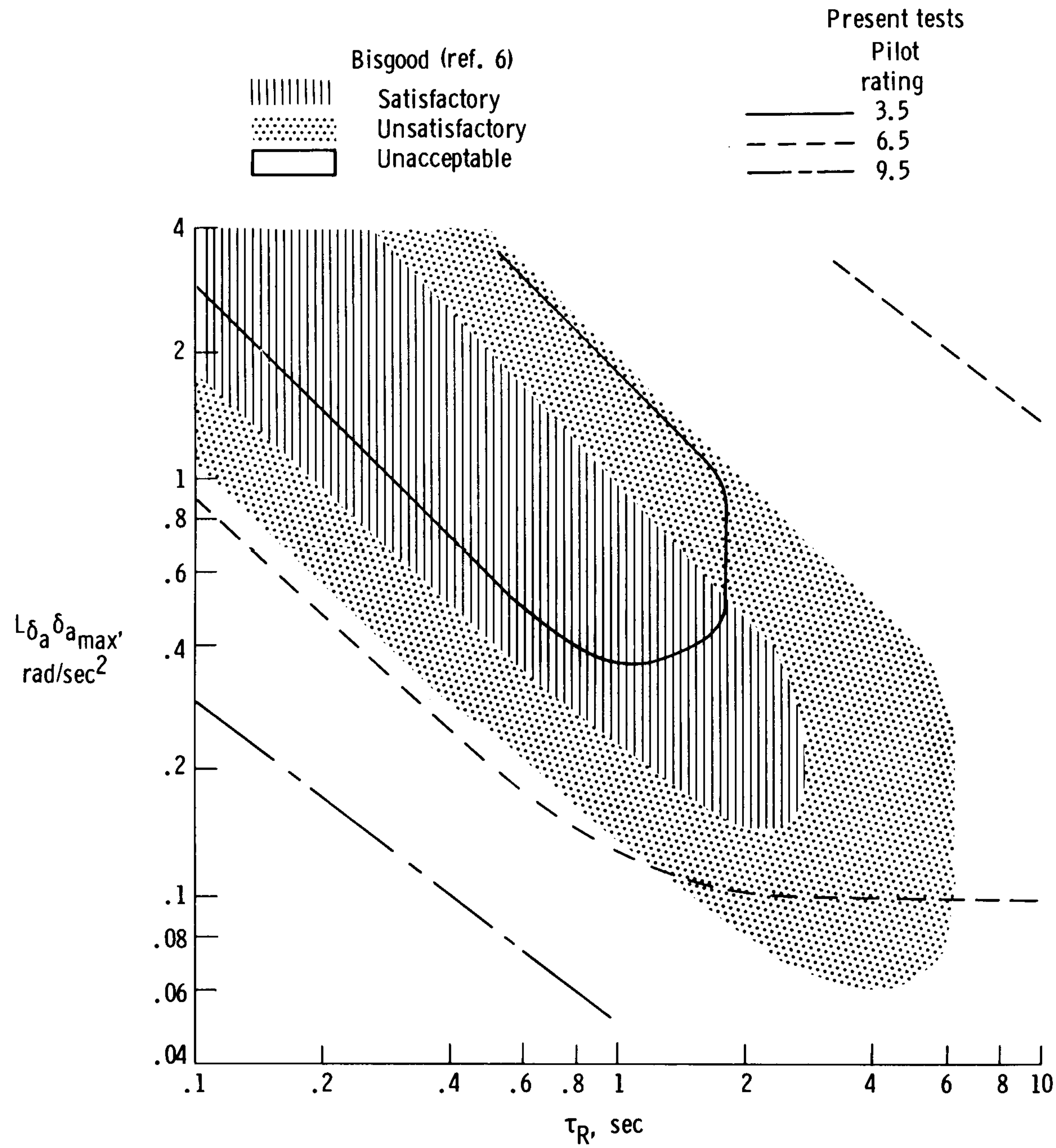


(a) Pilot selected wheel-force gradient as optimum; wheel force gradient range = 0.2 to 0.6 lb/deg (0.9 to 2.7 N/deg).



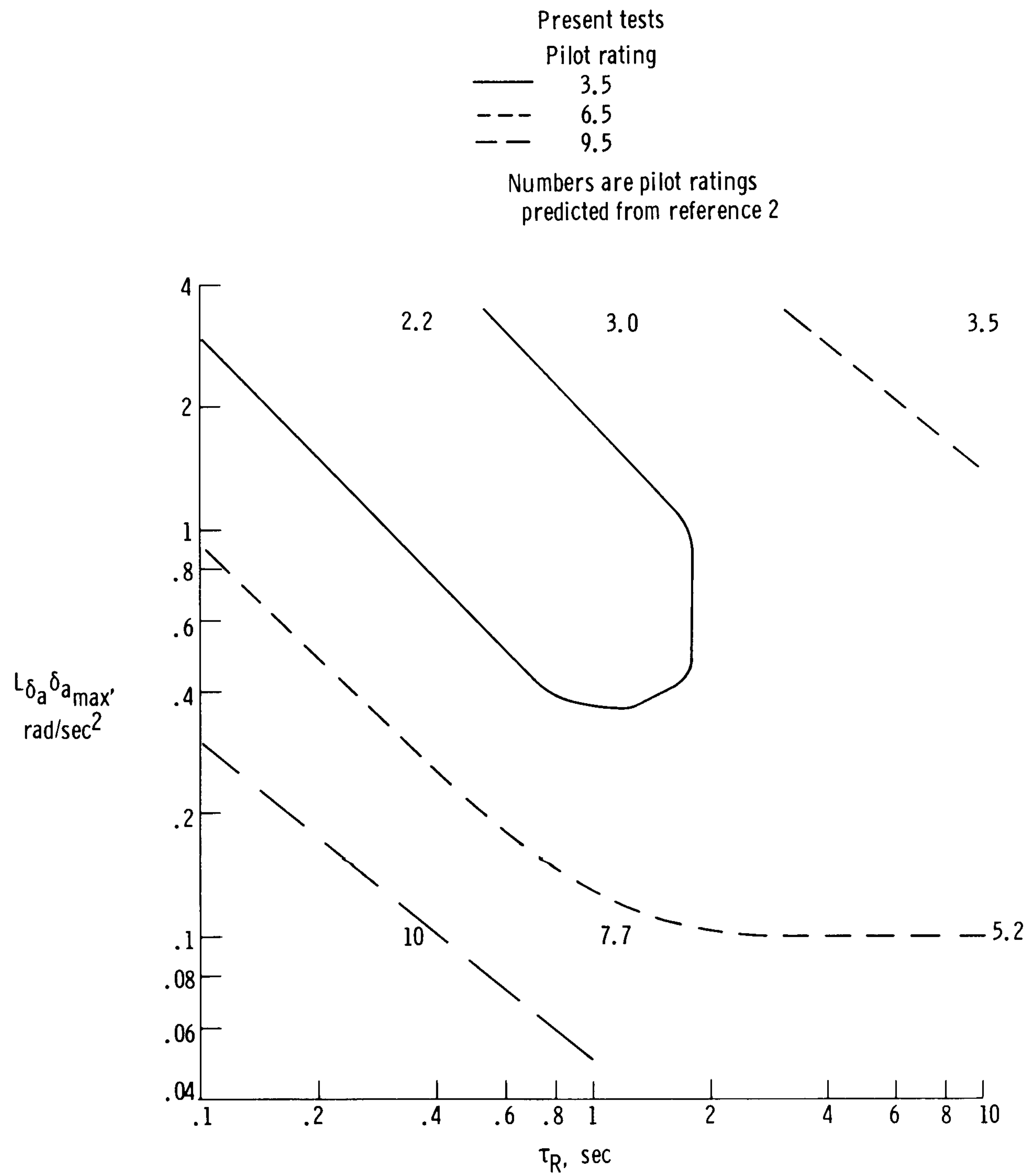
(b) Wheel force gradient 0.4 lb/deg (1.8 N/deg).

Figure 38. Comparison of pilot A and C ratings of selected optimum sensitivity during a special flight and the pilots' evaluations of control sensitivities for selected roll characteristics.



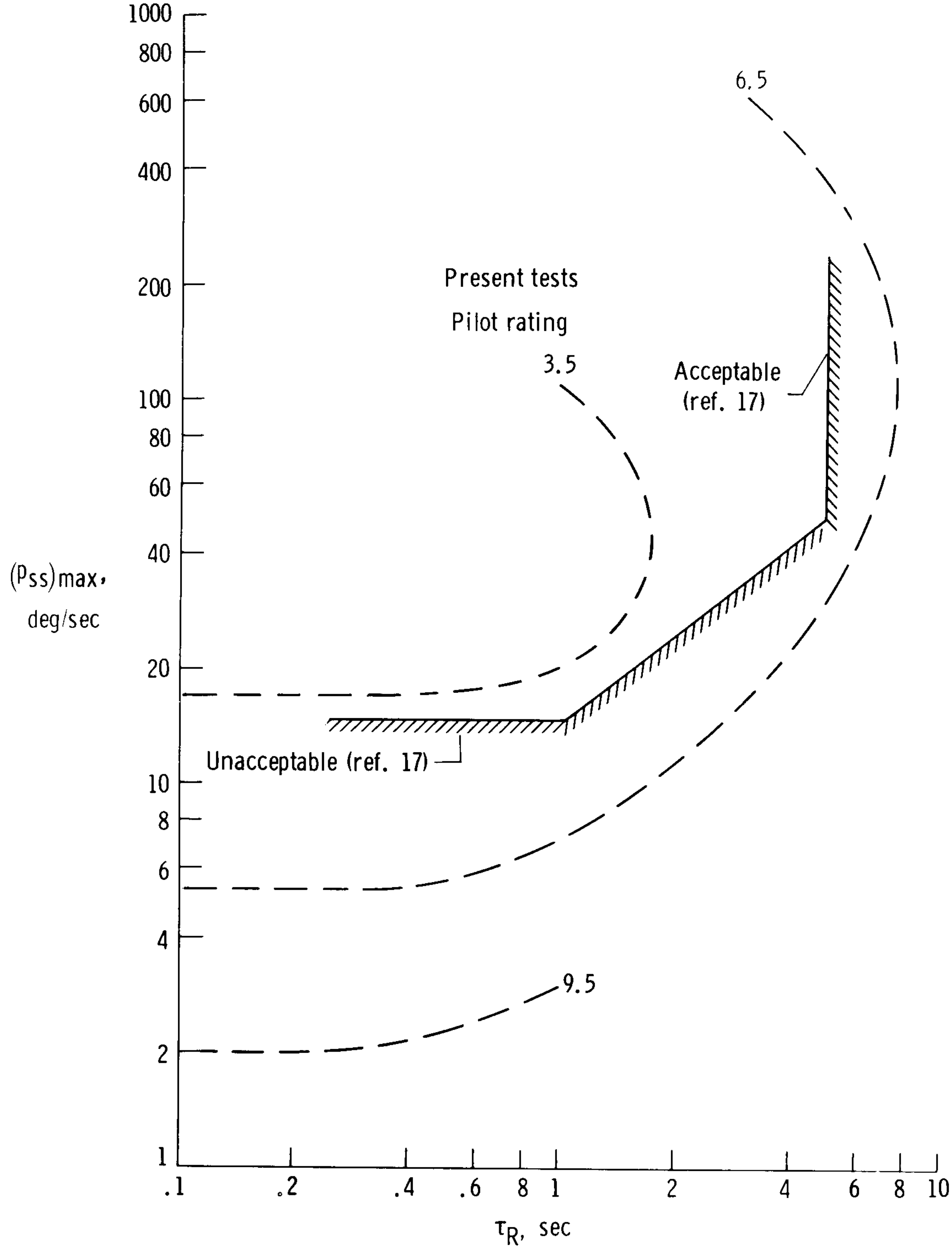
(a) Bisgood proposed criterion for approach condition.

Figure 39. Comparison of present results and referenced results.



(b) Prediction of reference 2.

Figure 39. Continued.



(c) Proposed criteria of reference 17.

Figure 39. Concluded.

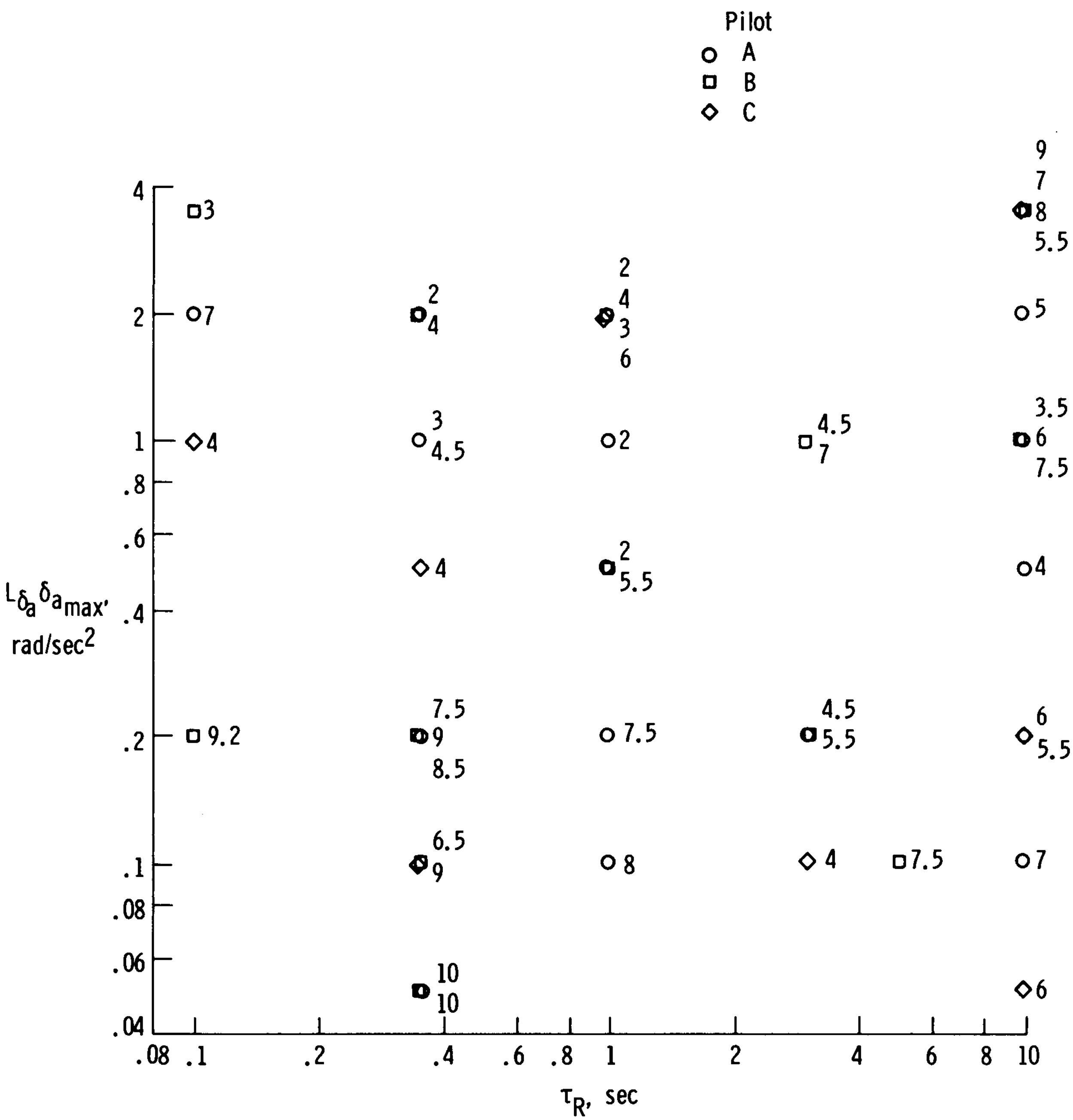


Figure 40. Summary of pilot ratings obtained during ground simulation.

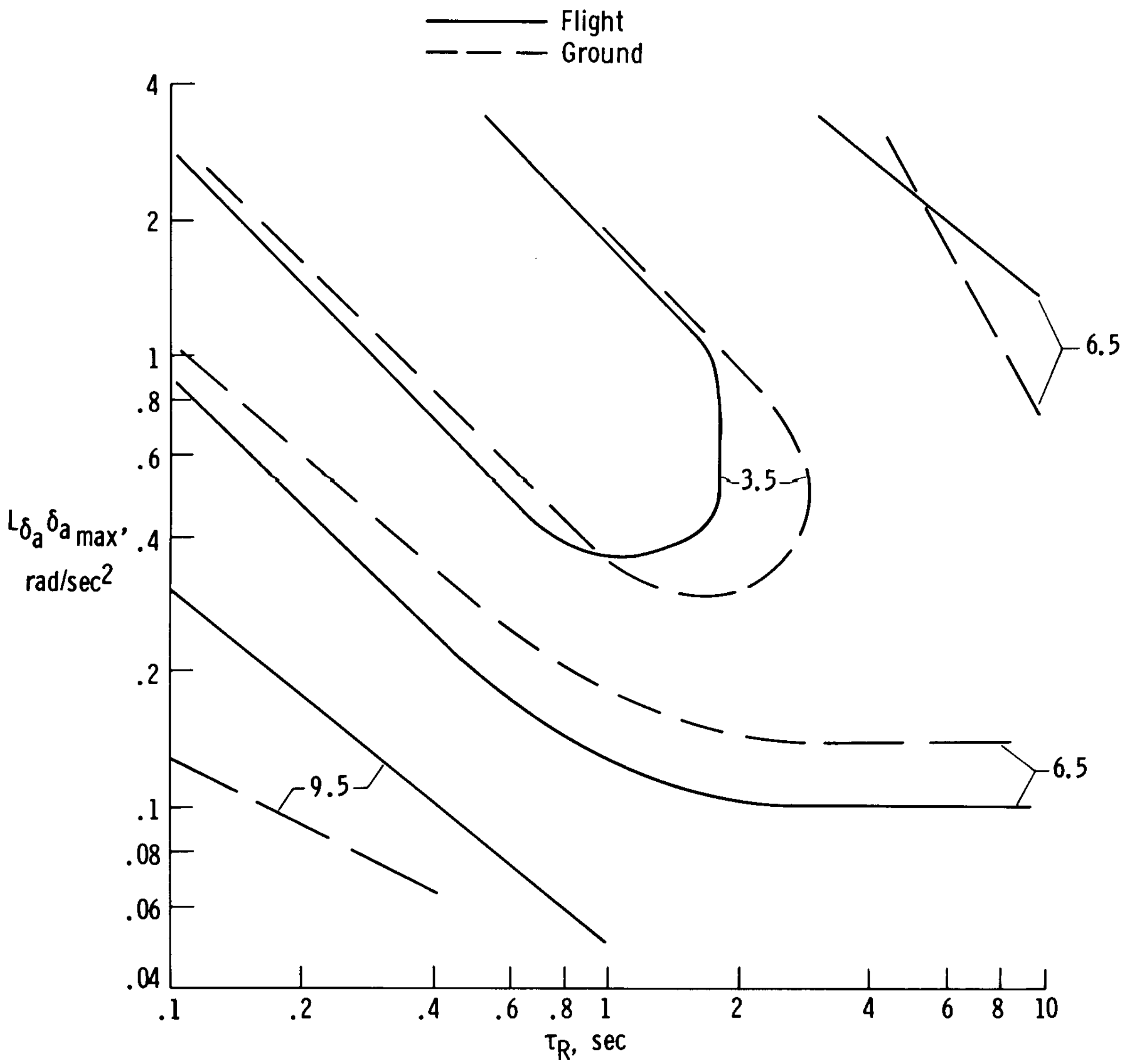


Figure 41. Roll criteria from ground simulation and comparison with flight-derived criteria.

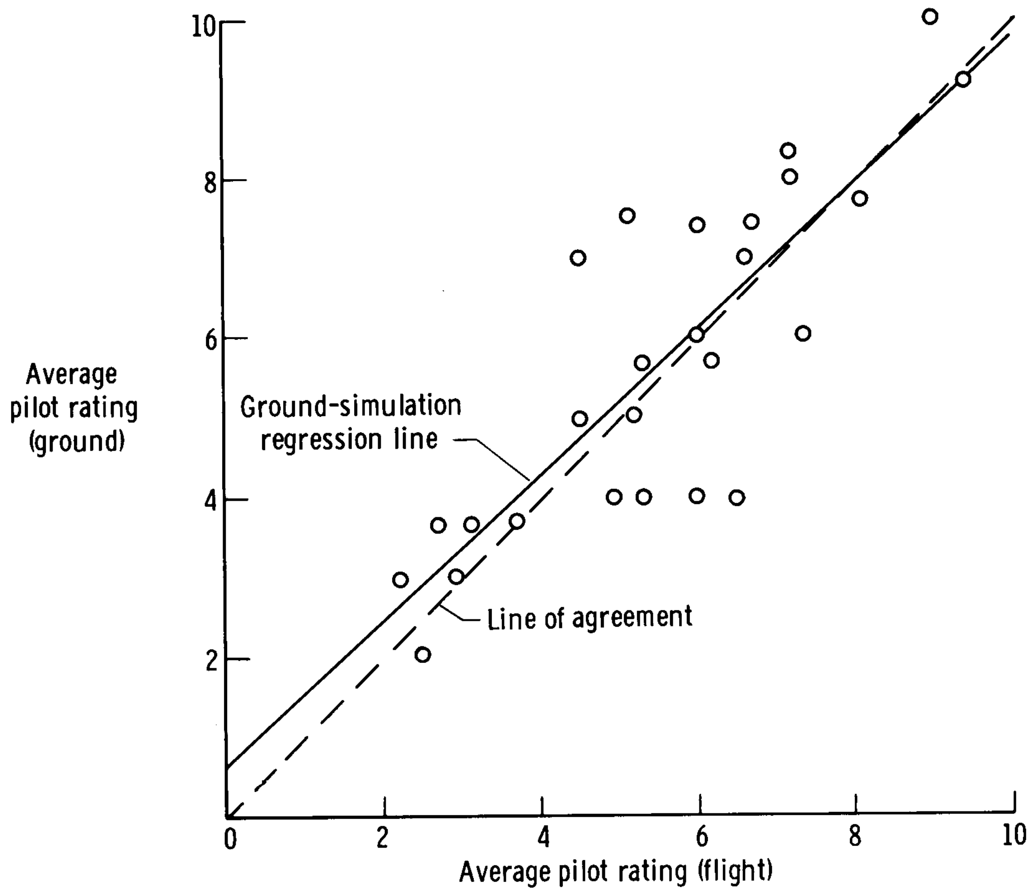
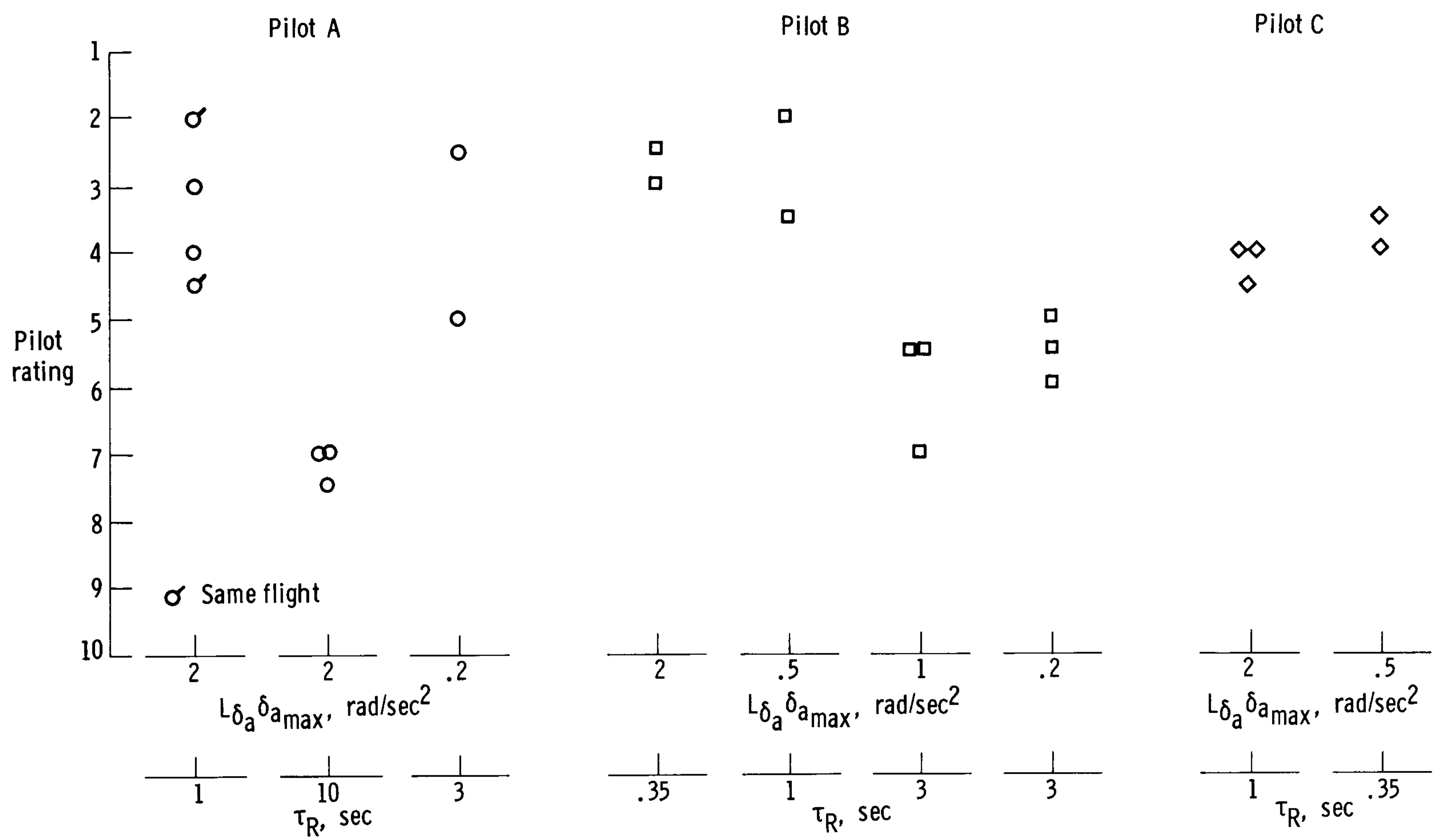
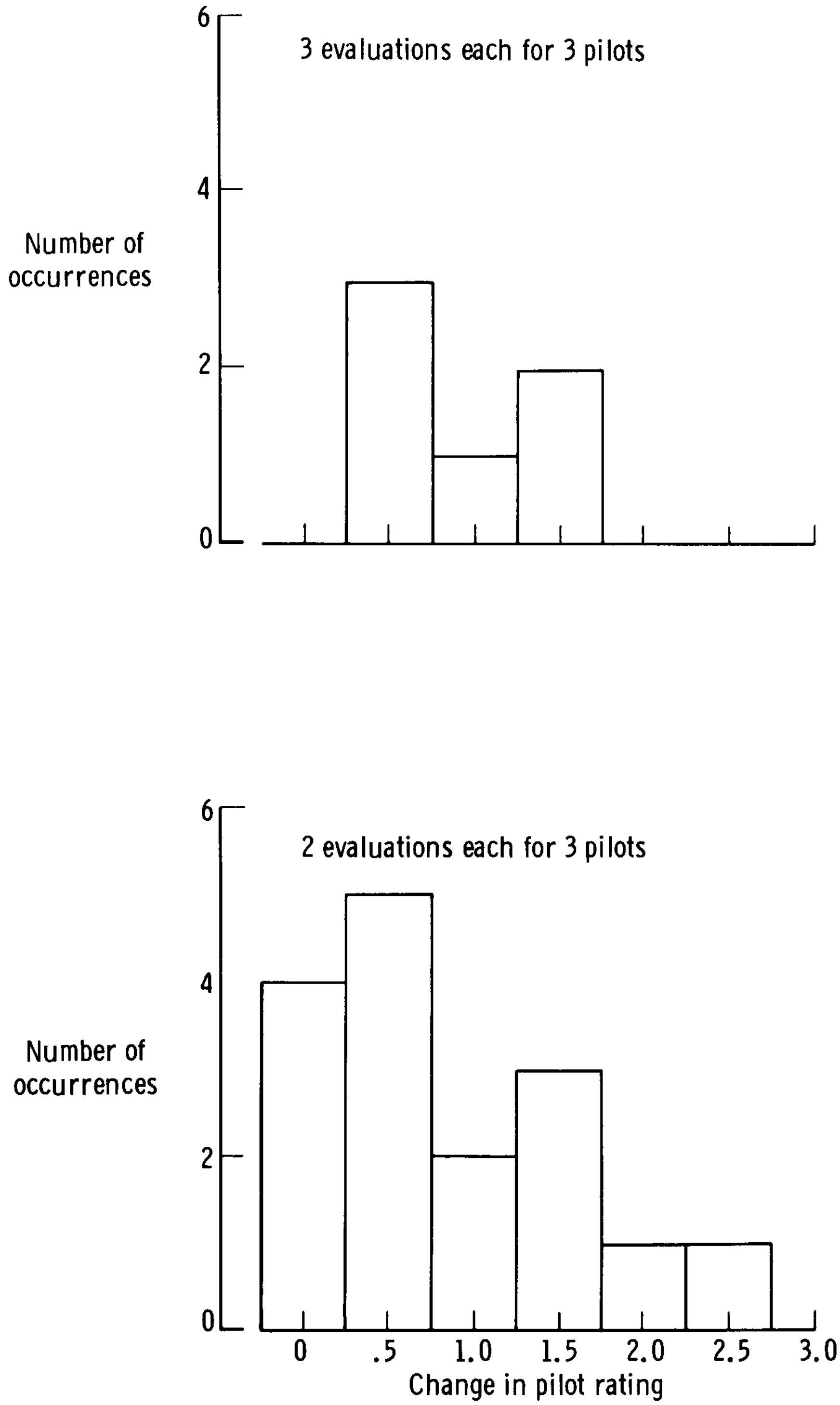


Figure 42. Comparison of average pilot rating for ground and flight evaluations.



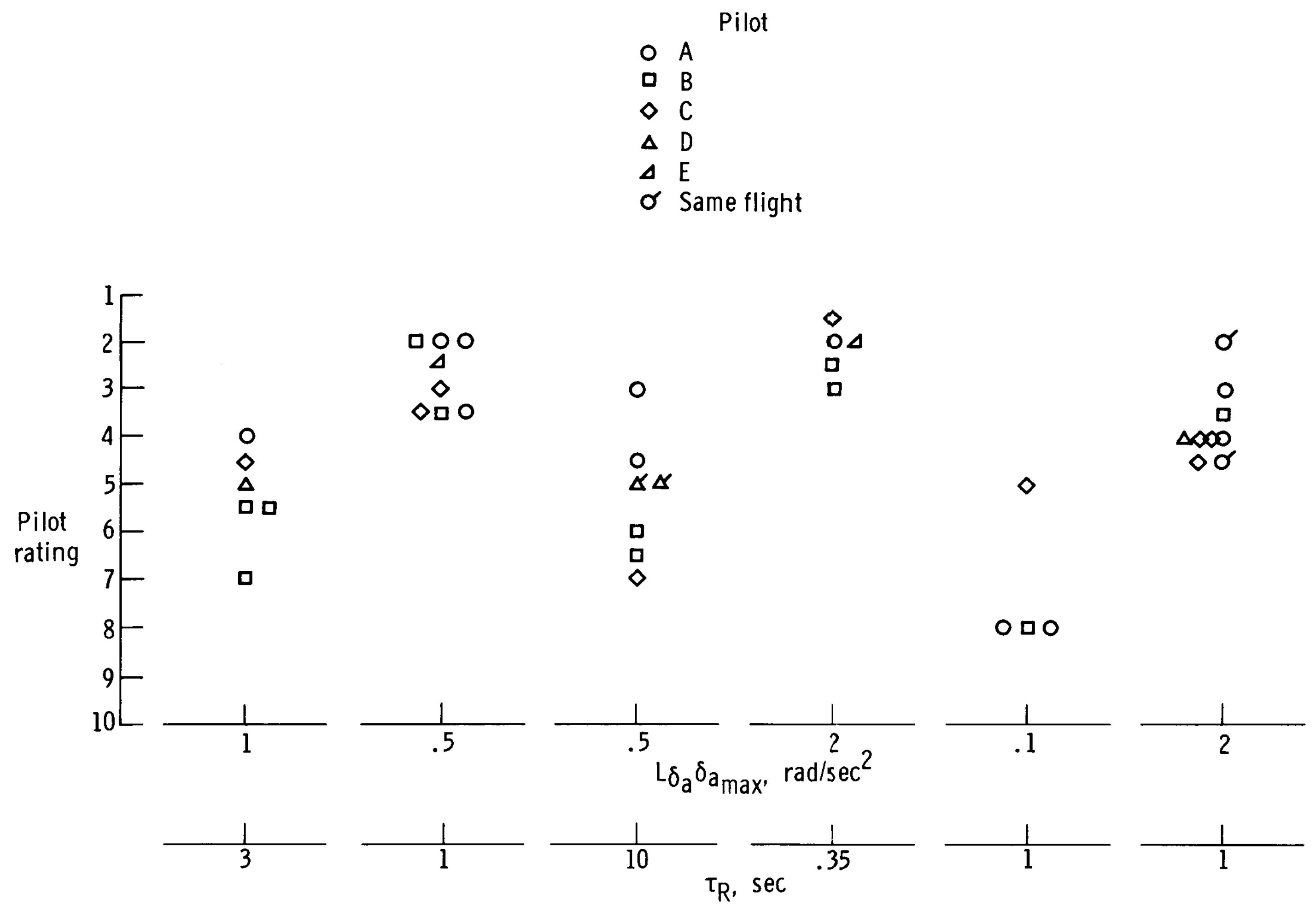
(a) Examples of intrapilot variation in pilot rating.

Figure 43. Intrapilot rating variability.



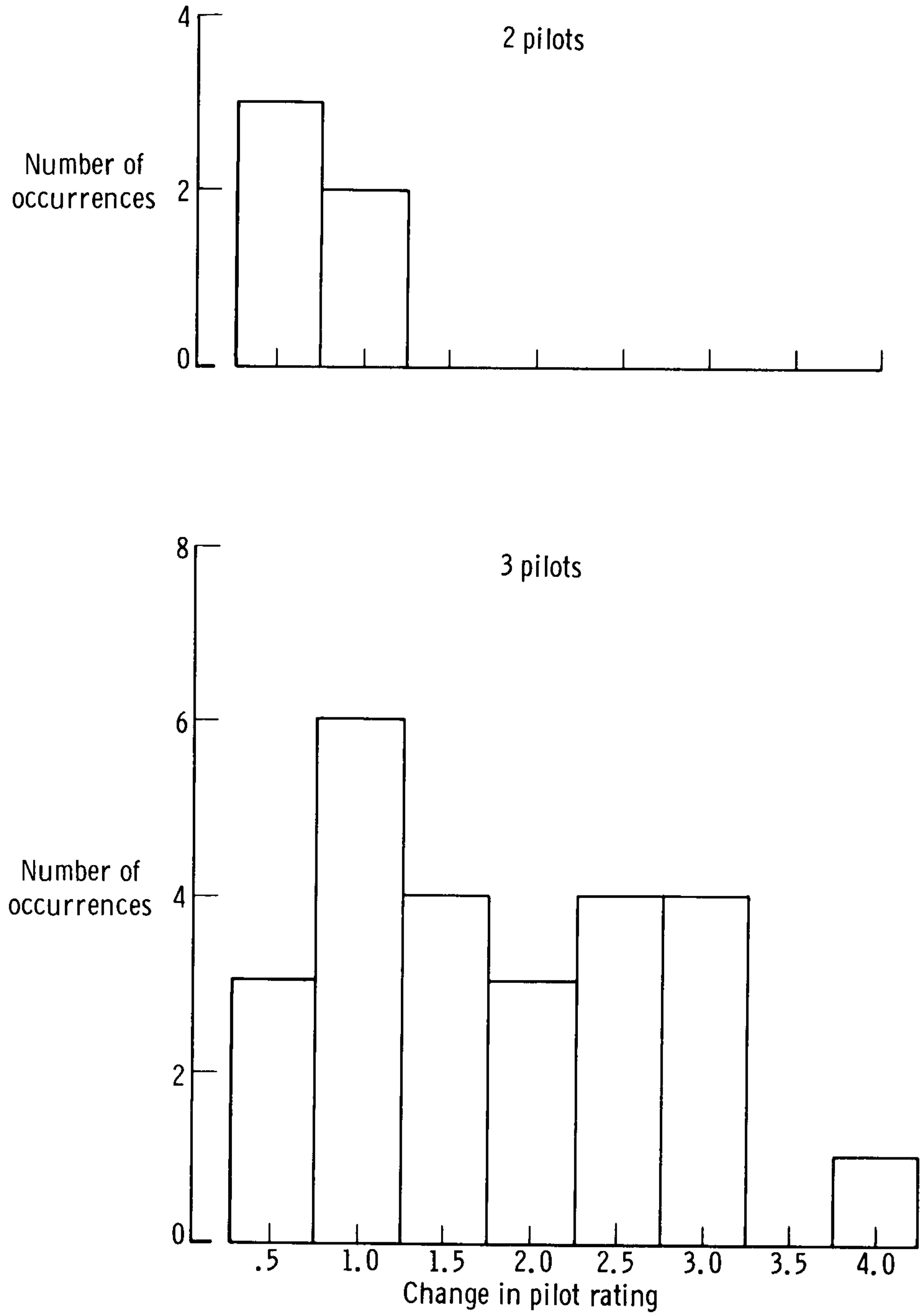
(b) Distribution of intrapilot variability.

Figure 43. Concluded.



(a) Examples of interpilot variation in pilot rating.

Figure 44. Interpilot rating variability.



(b) Distribution of interpilot variability.

Figure 44. Concluded.

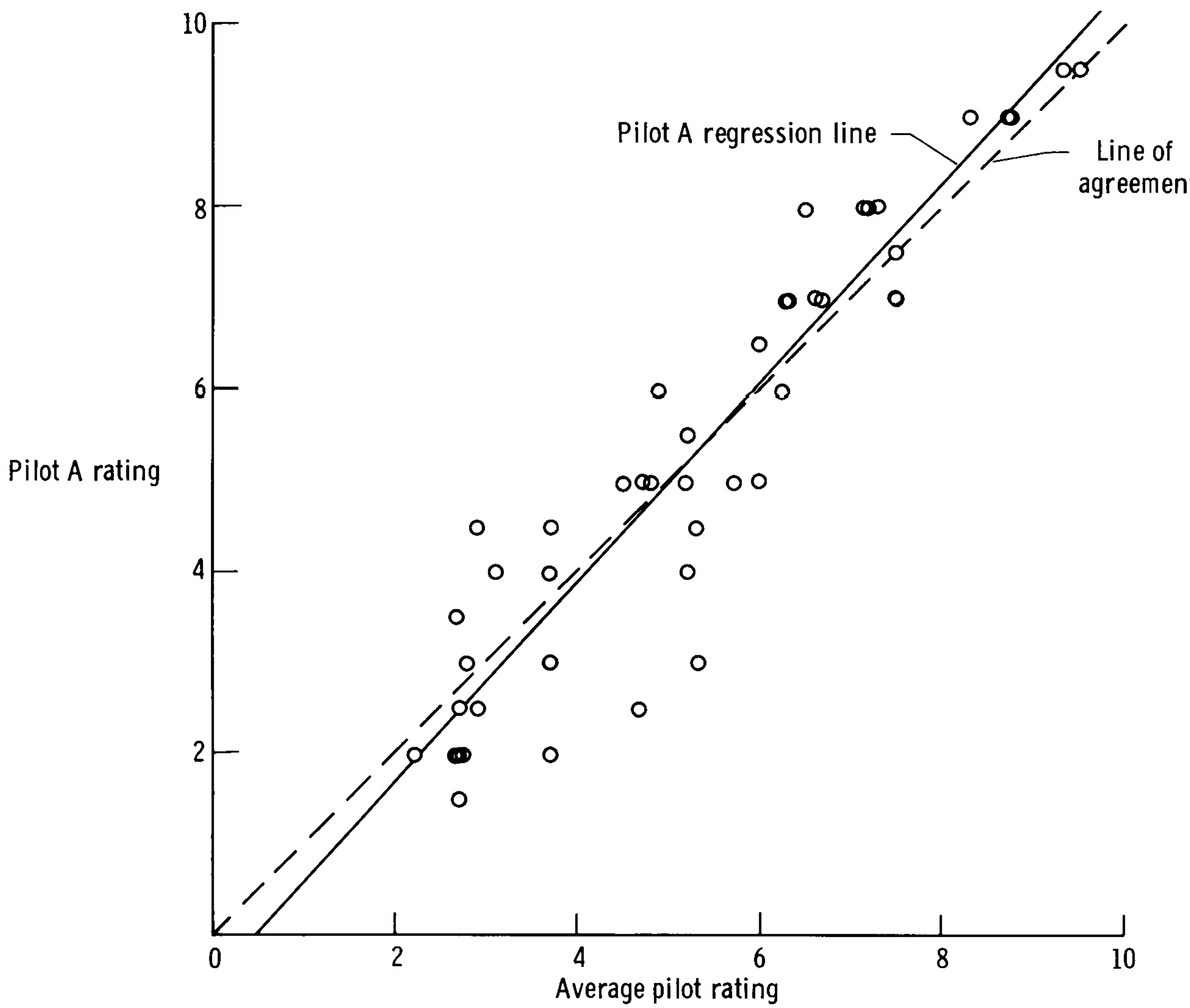


Figure 45. Comparison of pilot A ratings with the average of all pilots.

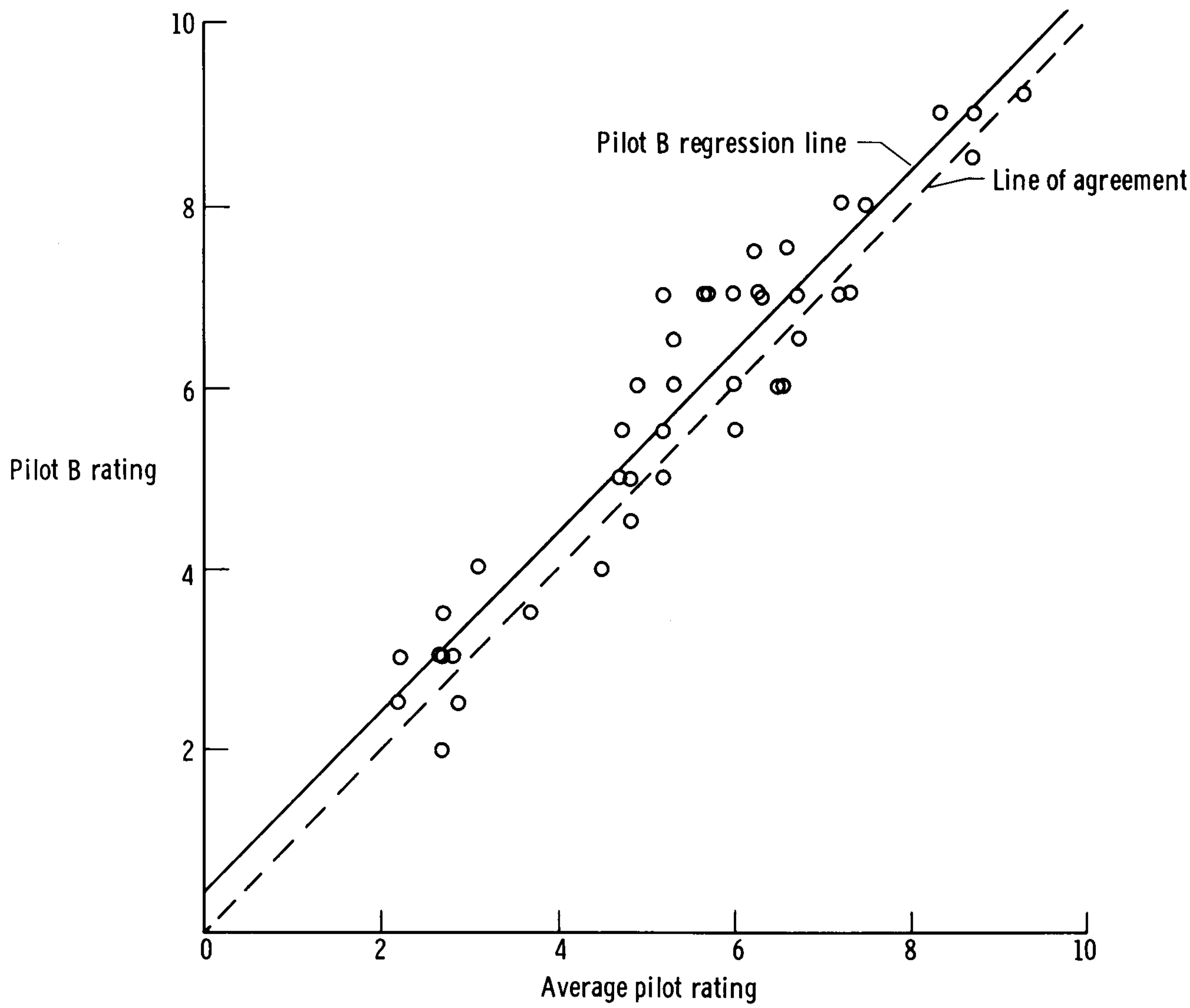


Figure 46. Comparison of pilot B ratings with the average of all pilots.

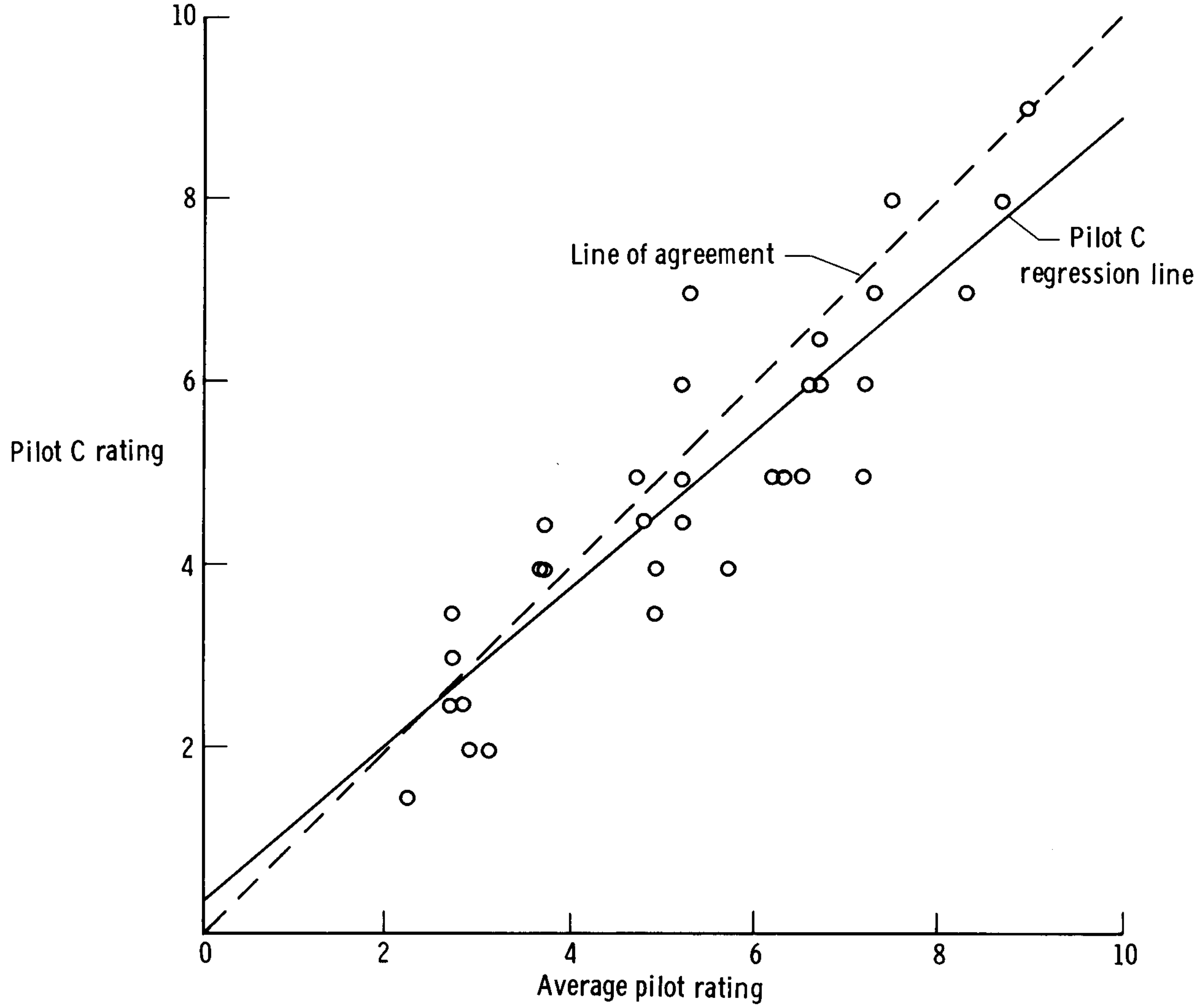


Figure 47. Comparison of pilot C ratings with the average of all pilots.

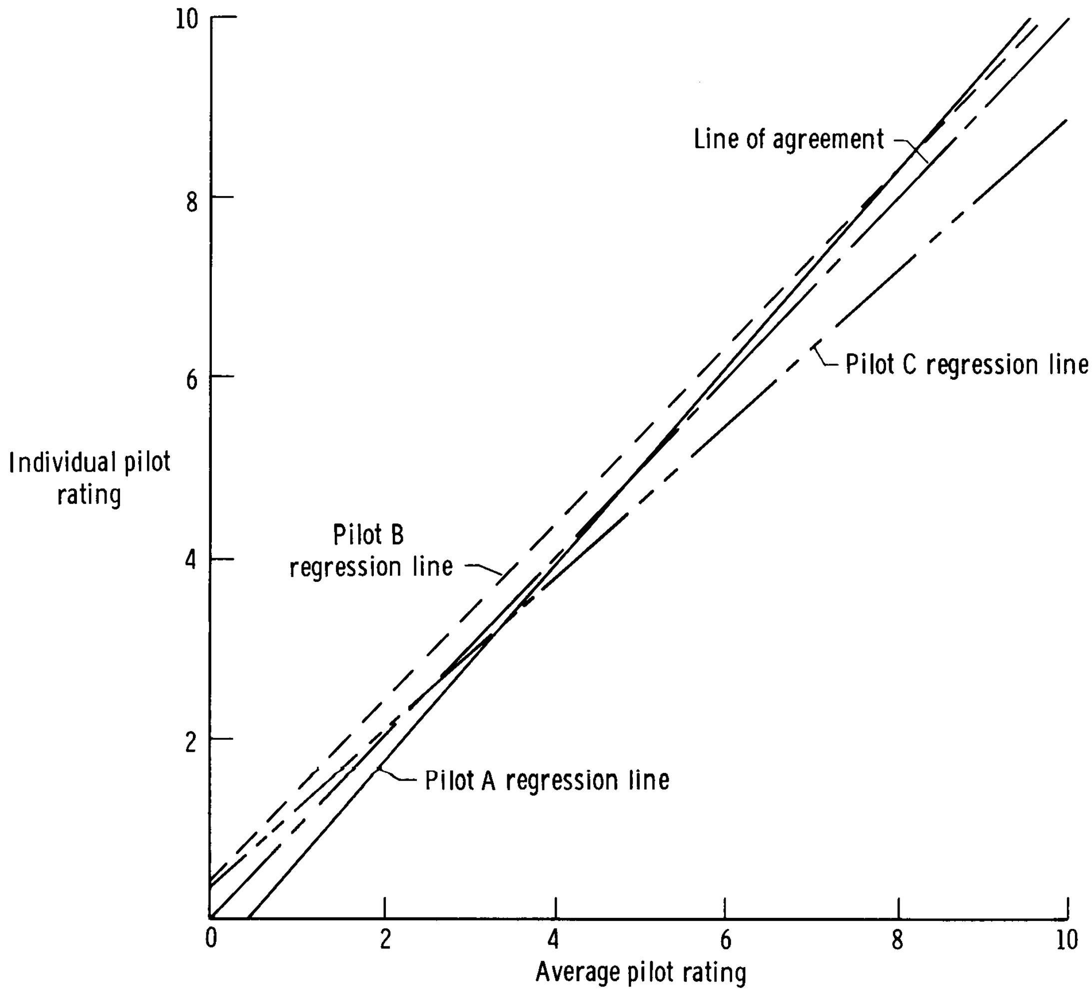


Figure 48. Comparison of pilot regression lines with line of agreement.

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